Enhancing Smart Grid Development in Thailand:
Smart Building, Smart Consumer, and Smart Policy Nexus

Von der
Fakultät Architektur, Bauingenieurwesen und Umweltwissenschaften
der Technischen Universität Carolo-Wilhelmina
zu Braunschweig

zur Erlangung des Grades einer
Doktor-Ingenieurin (Dr.-Ing.)
genehmigte

Dissertation

von
Jirapa Kamsamrong
geboren am 05.06.1987
aus Bangkok, Thailand

Eingereicht am 2 Juli 2019
Disputation am 17 Dezember 2019

Berichterstatter: Prof. Dr.-Ing. M. Norbert Fisch
Prof. Dr.-Ing. Christoph Menke

2020

- empty page -

Acknowledgement

This research would not have been possible without great support from a number of people. First of all, I am highly fortunate and grateful to have Prof. Dr.-Ing. M. Norbert Fisch and Prof. Dr.-Ing. Christoph Menke as my supervisors. Prof. Fisch always provides valuable and practical comments on my research. His guidance has been inspired me that research is not only in academic papers but can be applied in the real world. Prof. Menke has been my great supporter in many ways, not only for research, but also my life and career. He became my inspiration on how to manage work and life balance. He always makes sure that I am always happy during my studies in Germany, especially in the winter.

I am grateful to have Assoc. Prof. Dr. Chumnong Sorapipatana as my supervisor during the master's degree, who guided me on critical thinking. I would like to express sincere gratitude to Dr. Milou Beerepoot who inspired and motivated me to start the Ph.D. journey. I would like to thank Dr. Robert Himmler and EGS-Plan Bangkok Co., Ltd for providing me a case study for my research. It is an honor for me to receive a Ph.D. scholarship from Deutscher Akademischer Austauschdienst (DAAD), which made this research possible with financial support. I would like to thank the staffs and colleagues at Institut für Gebäude- und Solartechnik (IGS) for everything during my Ph.D. in Braunschweig.

I am very much grateful to my mother, father, and sister who live far away but always keep me warm with their love and support during the past four years. Finally, I would like to thank my husband for listening, offering me advice, and encouraging me when I face difficult times. My thanks and appreciation to all of them for being part of this journey and making this thesis possible.

- empty page -

Abstract

Thailand has been relying on fossil fuels in power generation, yet renewable energy is an attractive and alternative energy resource to mitigate their environmental impact. Smart grid technology can enhance renewable energy in the electricity system by integrating information communication technology (ICT) into the existing electricity network. Moreover, the smart grid also encourages the traditional consumer to become a proactive consumer and a prosumer. Residential and commercial buildings can perform as a power plant with an energy design concept by integrating renewable energy and energy storage system. However, there has been relatively little focus on how to enhance the residential sector in smart grid development in the context of Thailand. This research focuses on residential buildings only.

The technology assessment shows that energy efficiency measures (EEM) must be implemented to reduce the energy demand of the building. The integration of the PV system can decrease the amount of imported electricity from the public electricity grid network, where the energy storage system combination can increase the PV direct use. The Ice thermal energy storage system (ITES) is an appropriate energy storage system application that can provide cooling energy, which is the major energy consumer in residential building. The integration of EEM, the PV system, and the ITES system can reduce the primary energy demand by 87%, compared to the reference building without comprehensive energy concept design.

To allow the smart residential prosumers into the clean energy system development, the distribution system operator (DSO) should revise the grid code instead of limit the PV penetration rate in the low voltage (LV) network. The power quality assessment shows that the PV hosting capacity is limited up to 75%, which keeps the voltage level in the permissible range. The distributed energy storage system allows the PV prosumer to perform an active role by providing reactive power service to the system at the critical electricity feeder.

Energy costs are the major expenditure of a building's lifetime, and account for 70% of the total cost. The economic assessment reveals that the ITES is the most cost-effective investment option, where the battery energy storage (BES) system can become more attractive with incentive support and future cost reduction. The results from the consumer survey reveal that the willingness to pay (WTP) of the EEM and PV system in the detached single-family house is higher than the investment cost, which benefits both consumer and house developer.

Technology is a key driver for providing the energy service to the energy system, while consumer behavior and acceptance can increase technology adoption. Real-time energy consumption data can activate consumer behavior changes with the appropriate incentive program. The electricity price responsiveness varies by individual preference, and dynamic electricity pricing can increase the consumer's awareness of energy efficiency. The Thai government should encourage the residential sector to become a smart user by taking technology, consumer behavior background, and essential energy policy into account. The smart building, smart consumer, and smart energy policy nexus would be the key success factors for further smart grid development in Thailand.

Kurzfassung

Bisher deckt Thailand seine Stromerzeugung überwiegend durch fossile Brennstoffe, doch erneuerbare Energien sind eine attraktive und alternative Energiequelle, um die Auswirkungen auf die Umwelt zu mindern. Intelligente Netztechnik, sogenannte Smart Grid-Technologie, kann durch die Einbindung von Informations- und Kommunikationstechnologie die Integration von erneuerbaren Energien in das bestehende Stromnetz verbessern. Darüber hinaus ermöglicht ein intelligentes Netz auch traditionellen Verbrauchern, ihren Verbrauch proaktiv zu steuern oder zu sogenannten Prosumern zu werden. Wohn- und Gewerbegebäude können mit Hilfe eines Energiekonzepts durch die Integration von erneuerbaren Energien und Energiespeichern als Kleinkraftwerk fungieren. Allerdings gibt es in Thailand bisher wenig Analysen, wie man den Wohnungssektor für die Entwicklung intelligenter Netze nutzbar machen kann. Diese Forschungsarbeit konzentriert sich daher ausschließlich auf Wohngebäude.

Die Technologiebewertung zeigt, dass Energieeffizienzmaßnahmen (EEM) umgesetzt werden müssen, um den Energiebedarf der Gebäude zu reduzieren. Die Integration eines Photovoltaik (PV)-Systems kann die Menge an importiertem Strom aus dem öffentlichen Stromnetz verringern, wobei die Kombination mit einem Energiespeicher den PV-Autarkiegrad erhöhen kann. Ein thermischer Energiespeicher basierend auf Eis (ITES) ist eine geeignete Speicheranwendung, um Kühlenergie bereitzustellen, die der Hauptenergieverbraucher in Wohngebäuden ist. Durch die Integration von EEM, dem PV-System und dem ITES-System kann der Primärenergiebedarf um 87% reduziert werden, verglichen mit einem Referenzgebäude ohne umfassendes Energiekonzept.

Um intelligenten Haushaltskunden die Nutzung sauberer Energiesysteme zu ermöglichen, sollte der Verteilnetzbetreiber die Netzanschlussrichtlinien überarbeiten, anstatt den Ausbau von PV-Anlagen im Niederspannungsnetz zu begrenzen. Die vorliegende Forschungsarbeit zeigt, dass die PV-Aufnahmekapazität auf bis zu 75% ausgeweitet werden kann, ohne dass Spannungsgrenzen verletzt werden. Der dezentrale Energiespeicher ermöglichst es zudem dem PV-Prosumer, durch Blindleistungseinsatz eine aktive Rolle im Stromsystem einzunehmen und Spannungsprobleme in kritischen Leitungssträngen zu reduzieren.

Die Energiekosten stellen den größten Kostenaufwand während der Lebensdauer eines Gebäudes dar und machen 70% der Gesamtkosten aus. Die wirtschaftliche Bewertung zeigt, dass das ITES die kostengünstigste Investitionsoption ist und das Batteriespeichersystem (BES) durch Anreize und künftige Kostensenkungen an Attraktivität gewinnen kann. Die Ergebnisse der durchgeführten Verbraucherbefragung zeigen, dass die Zahlungsbereitschaft für die EEM und das PV-System in Einfamilienhäusern höher ist als die Investitionskosten, was sowohl dem Verbraucher als auch dem Bauherrn des Hauses zugutekommt.

Neue Technologien sind zentrale Elemente, um die Bereitstellung von Energiedienstleistungen im Energiesystem zu ermöglichen. Jedoch sind auch Nutzerverhalten und -akzeptanz wichtig, um die Verbreitung der Technologie zu erhöhen. Echtzeitdaten über den Energieverbrauch können Verhaltensänderungen beim Verbraucher mit Hilfe entsprechender Anreizprogramme bewirken. Die Reaktion auf Strompreisschwankungen variiert je nach individueller Präferenz. Außerdem kann eine dynamische Strompreisgestaltung das Bewusstsein des Verbrauchers für Energieeffizienz erhöhen. Die thailändische Regierung sollte den Einsatz von Intelligenz im Wohnungssektor fördern und dabei Technologien, Verbraucherverhalten und wesentliche energiepolitische Aspekte berücksichtigen. Die Verflechtung von intelligenten Gebäuden, intelligenten Verbrauchern und intelligenter Energiepolitik ist ein Schlüsselfaktor für den Erfolg von intelligenten Netzen in Thailand.

Contents

List of Figures

List of Tables

- empty page -

Chapter 1

Introduction

1.1 Introduction

Excessive fossil fuel consumption intensifies climate change concerns regarding future power sector planning. For the past two decades, Thailand has relied heavily on natural gas as the main primary energy in the power generation system. Although Thailand has domestic natural gas resources, they are limited and have been decreasing over time due to consumption in other sectors. Consequently, Thailand must import natural gas from abroad mainly to supply the power generation sector. Regarding past experiences in Thailand, the effort to build new coal-fired and nuclear power plants always faces a strong protest from the public due to environmental concerns (Kamsamrong & Sorapipatana, 2014). It is a challenge for the Thai government to maintain the energy supply security of the country.

Renewable energy (RE) has become an attractive solution for a future power system because of its environmentally friendly advantages and rapid cost reduction. However, power quality concerns have been questioned from the electric utility due to high reverse power flow on some critical existing electricity networks, which are not able to accommodate a high penetration of variable renewable energies (VRE), such as wind and solar energy. The mismatch between energy supply and demand in the residential sector may cause problems of voltage rise due to the reverse power flow in the low voltage (LV) network (IEA, 2014a). The energy storage system and energy efficiency measure can play significant roles in overcoming the discrepancy of the VRE and the energy demand.

A smart grid offers advanced technology to support the VRE in the electricity system by integrating information and communication technology (ICT) for effective management. Electric utilities in Thailand have developed smart grid roadmaps but are currently focusing mainly on technology interoperability in the power system. The smart meter is one of the smart grid technologies which is being implemented to the end-user for real-time monitoring. However, the consumers still have no clue of its true advantage and the effects to their daily lifestyle.

The smart grid also enables the traditional consumer to become the proactive consumer; who can manage electricity demand through real-time data and price signals, and the prosumer; who can produce electricity and sell the excess energy to the electricity network. The residential building can perform as a power plant by integrating the renewable energy resource and the energy storage system to contribute energy services to the electricity grid network (Fisch et al., 2013).

In Thailand, residential consumers are still facing several limitations to become prosumers in both technical and non-technical aspects such as consumer behavior and policy support. The high potential integrated technology in the building can overcome the technology limitation, while energy policy and regulations can support the small players to compete with the large players under fair rules. The techno-economic, consumer, and policy nexus approach would be the key success factor for further smart grid development in Thailand.

1.2 Problem definition

The single-family house represents most residential buildings in Thailand, and accounts for 72% of total households (NSO, 2010). The numbers of new construction for single-family houses is higher than other residential buildings (e.g. condominium, townhouse), especially in Bangkok and surrounding areas (NSO, 2018). However, the energy design concept is still untapped on a commercial scale due to the lack of regulation and interest from the consumer and house developers. In addition, there is no law enforcement of building energy codes for single-family houses in Thailand yet.

The traditional prosumer, by installing the PV system on the roof, can become the smart prosumer by integrating energy design in the building. But, the question arises of what are the potential technology options in the Thailand context. Techno-economic feasibility with policy support can enhance new technology adoption for residential consumers in Thailand.

Smart grid allows traditional consumers to become prosumers, but without energy design integration may cause power quality control challenges to the electric utility due to the mismatch between electricity demand and the supply of the building. Typically, the Thai electricity utility limits feed-in electricity from residential PV prosumer by 15% of rated distribution transformer capacity. Conversely, the electricity utility must provide an active grid code to allow clean energy from small players in the energy system, rather than traditional grid code enforcement.

In addition, several studies have indicated that non-technical issues, such as consumer acceptance, are one of the reasons why energy policy deployment has failed (Naus et al., 2014; Krishnamurti et al., 2015; Döbelt et al., 2015; Colak et al., 2014; Jirapornanan, 2010; IEA, 2011). Introducing new technology to the consumer could not only focus on technology advantage to the electricity utility, but must also consider on how the technology affects the consumer's daily life. The lack of attention on consumer behavior for new technology integration can become an uncertain factor in the smart energy solution deployment. Significant relationships between techno-economic, consumer behavior, and energy policy are essential to address the appropriate approaches for residential sector participation in the smart grid development of Thailand.

1.3 Objectives

This research aims to investigate and address the integrated technology potential applications for the detached single-family building in Thailand by taking the techno-economic and consumer dimensions into account to recommend a new energy policy intervention for enhancing the residential sector in smart grid development. The scope of this research focuses on detached single-family buildings in the residential sector of Thailand.

1.4 Research questions

Following the research objective, the research questions can be divided into three parts as follows:

1.4.1 Technological aspects

The first part of the research is the assessment of technology potential for the detached single-family building in Thailand, and covers the following research questions:

1) What lessons can be learned from other countries for integrated technologies in the residential building? (Chapter 3)
2) What is the energy consumption baseline of the reference detached single-family building in Thailand? (Chapter 3)
3) What energy savings and carbon dioxide emissions can be expected from the integrated technology packages in the detached single-family building? (Chapter 4)
4) How can the existing electricity grid handle the high penetration of PV integration and what are the active control measures to replace the conservative technical regulations? (Chapter 5)

1.4.2 Economic aspects

The second dimension concerns the economic aspect with the following questions:

5) What is the economic feasibility of the integrated technology package for the detached single-family building in the context of Thailand? (Chapter 6)
6) What is the willingness to pay for the Thai consumer for the integrated technology in the detached single-family building? (Chapter 6)

1.4.3 Consumer and policy aspects

The third part aims to address the potential policy intervention for long-term consumer behavior change. The electricity industry structure is also at interest in this research. The research questions cover:

7) What is the current Thai consumer perception towards the smart grid? (Chapter 7)
8) What is the policymaker perception in Thailand towards smart grid development under the existing electricity market? (Chapter 7)
9) What are the energy policy inventions to enhance the traditional consumer to become a proactive consumer and the prosumer? (Chapter 7)

1.5 Research methodology

The research framework is divided into eight steps as follows (Figure 1.1)

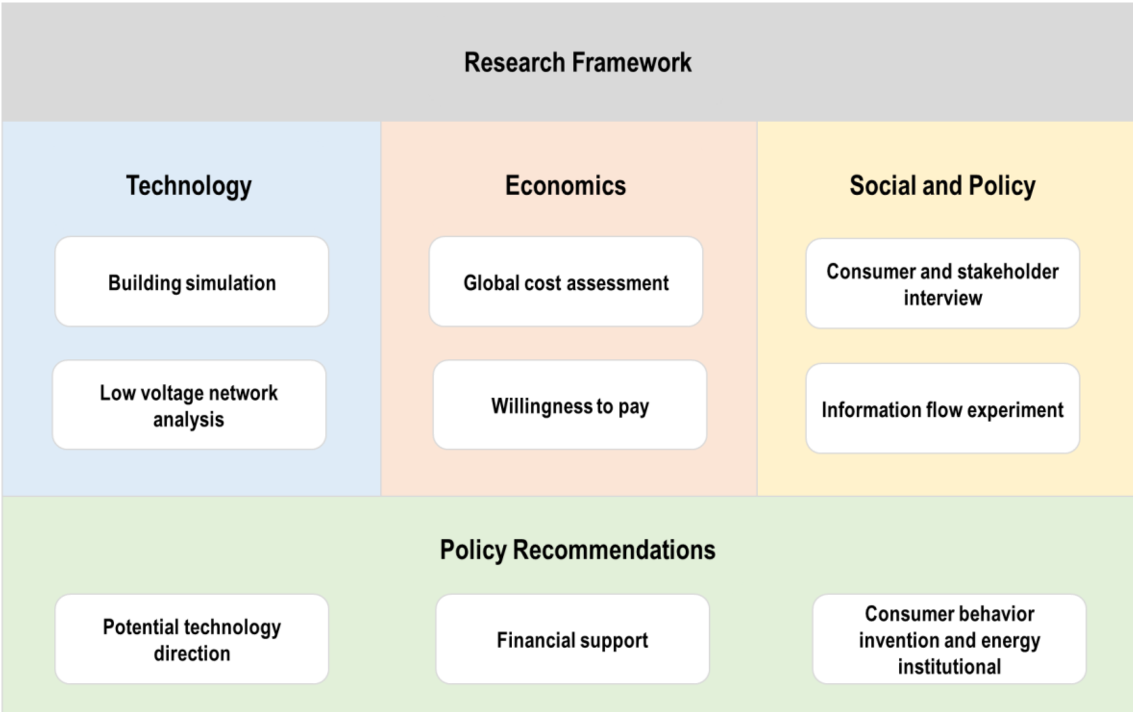


Figure 1.1 Research framework

First, the research starts with an overview of the current energy situation and energy policy in Thailand, and then reviews the potential technology applications for the end user in the smart grid context.

Second, the stakeholder and consumer interviews are conducted to foresee consumer perception and policymakers' vision toward smart grid development

Third, the detached single-family building in Bangkok represents the reference building in this research. The integrated technologies are investigated and compared with the reference building of energy performance and energy services to smart grid development.

Fourth, costs and benefits are assessed over whether this technology is economically feasible and requires an additional incentive. The willingness to pay can address the Thai consumer choice possibility for buying an integrated technology package in the detached single-family building.

Fifth, the research investigates the power quality from high PV integration in the LV network to identify the possible PV hosting capacity. Active control strategies are proposed for future grid code revision in Thailand.

Sixth, the research examines the current status of consumer behavior and perception toward smart grid development. The barriers and key drivers can identify the necessary policy interventions for consumer behavior change.

Seventh, the existing electricity industry structure in Thailand is reviewed as to whether it can accelerate the smart grid development in Thailand by taking the stakeholder's interview result into the analysis.

Eighth, energy policy recommendations are proposed for enhancing the residential sector of future smart grid deployment in Thailand, which consists of the potential technology application development direction, essential incentive program, consumer behavior change inventions, and energy institutional collaboration.

1.6 Simulation software

This research uses three-simulation software for different technical assessment purposes (Figure 1.2).

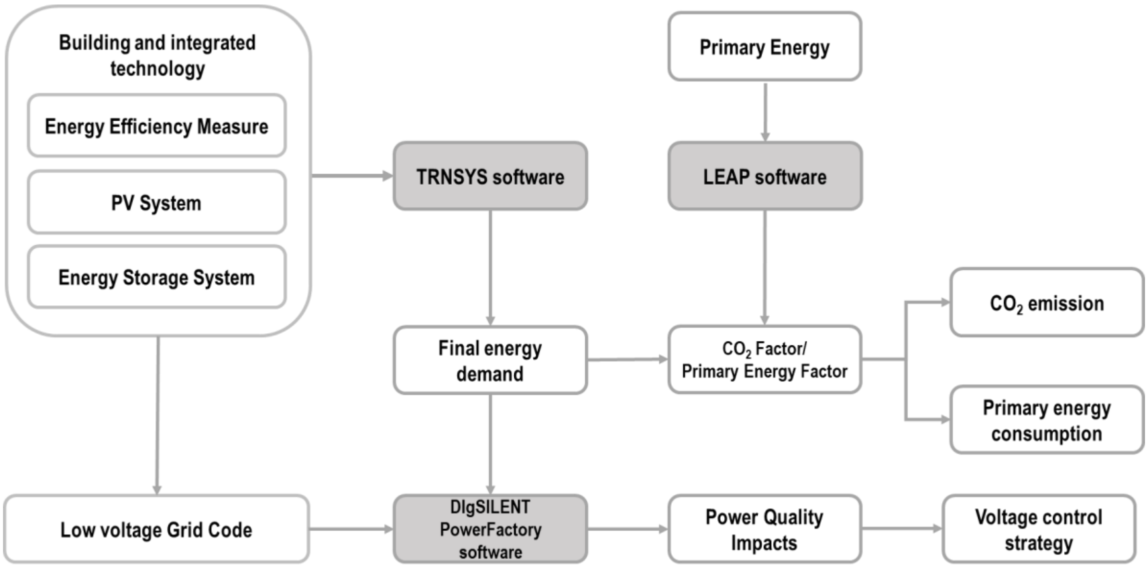


Figure 1.2 Simulation software in this research

First, the building is simulated by TRNSYS software version 17 for a 15-minute interval to assess and compare energy performance between the reference building and alternative buildings with the integrated technology package. The TRNSYS software is a powerful tool to simulate the building behavior in both a thermal and electrical system with massive libraries (Klein S.A. et al., 2017).

Second, the environmental impact and levelized cost of electricity (LCOE) in the power sector are assessed by the Long-range Energy Alternative Planning (LEAP) software, which is developed by the Stockholm Environment Institute (SEI) (Heaps, 2016). The LEAP software is widely used for energy planning and climate change mitigation assessment in national and regional levels.

Third, the DIgSILENT PowerFactory software investigates the power quality impacts from the PV integration in the LV network. The DIgSILENT PowerFactory software is state of the art for power system analysis, which is widely used by electricity utility companies worldwide (DIgSILENT, 2017).

1.7 Organization of the research

The research organization is divided into eight chapters. Chapter 2 introduces the background information of the energy situation and energy market structure for the readers to understand the energy context and development in Thailand. Chapter 3 presents the literature review of technology implications and policy lessons learnt. Chapter 4 examines the energy performance and environmental impact of technology applications for the single-family building. Chapter 5 investigates the power quality impacts in a low voltage electricity network with high PV penetration. Chapter 6 assesses the economic feasibility for integrated technology options and the likelihood of willingness to pay for it by the Thai consumer. Chapter 7 introduces the new consumer-behavior-change interventions and suggests the essential energy policy and incentive program supports for enhancing the residential sector in further smart grid development. Finally, the summary of this research is presented in Chapter 8.

Chapter 2

Overview of the Energy Situation and Energy Policy in Thailand

2.1 Introduction

The energy security issue is a challenge for future energy system planning in Thailand. Availability, accessibility, affordability, and environmentally friendly dimensions must be taken into consideration into a low carbon society development. Increasing the renewable energy share in the energy system has challenges for the policymakers in technical and non-technical dimensions, e.g. regulatory and incentive supports.

This chapter illustrates the energy situation, energy policy, and energy industry structure of Thailand. The background information can lead the readers to foresee why the smart grid is necessary for Thailand and what dimensions are essential for smart grid development in Thailand.

2.2 General information of Thailand

2.2.1 Geography

Thailand is located in Southeast Asia (SEA) region (Figure 2.1). The total area of Thailand is approximately 513,120 km^2 and the capital of Thailand is Bangkok. Thailand can be divided into five regions: north, east, northeast, central and south. The north part of Thailand connects to Myanmar and Laos, the west connects to Andaman sea and Myanmar, the east connects to Laos and Cambodia, and the south connects to Malaysia and the Gulf of Thailand.

Figure 2.1 Geography of Thailand

2.2.2 Population and economy

There are two ways to measure and compare gross domestic product (GDP) between countries, which are real GDP and GDP at power purchase parity (PPP). The real GDP represents economic output of a country by taking the effects of inflation or deflation into account. The real GDP illustrates the growth of a country over time; the GDP PPP is often used to compare economic productivity between countries. Generally, the GDP PPP is measured in United States dollars (US$) as a reference currency.

In 2018, the gross domestic product at power purchase parity (GDP PPP) of Thailand was US $1,234 billion and ranked 19th, while Germany ranked the fifth in the world, which accounted for US $4,187 billion (Figure 2.2). The population in Thailand was 69 million people, while in Germany it was 83 million people (The World Bank, 2017; BMWi, 2019). The average population growth rate in Thailand is approximately 0.3% and the average family size is four persons per household (NSO, 2017).

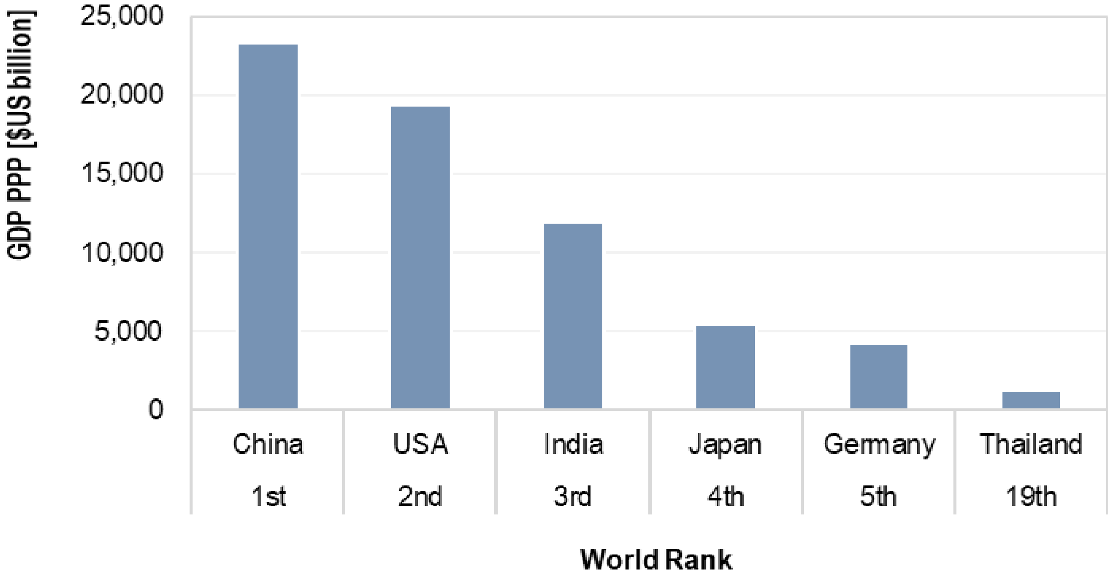


Figure 2.2 Comparison of GDP PPP between Thailand and top five countries in the world (The World Bank, 2017; BMWi, 2019)

2.2.3 Climate

Thai climate is defined as tropically wet. The climate in Thailand can be divided into three seasons: summer, rainy, and winter. The average temperature ranges between 25 ^{o}C to 30 ^{o}C (Meteonorm, 2016). The relative humidity of Thailand is above 60% throughout the year (Figure 2.3).

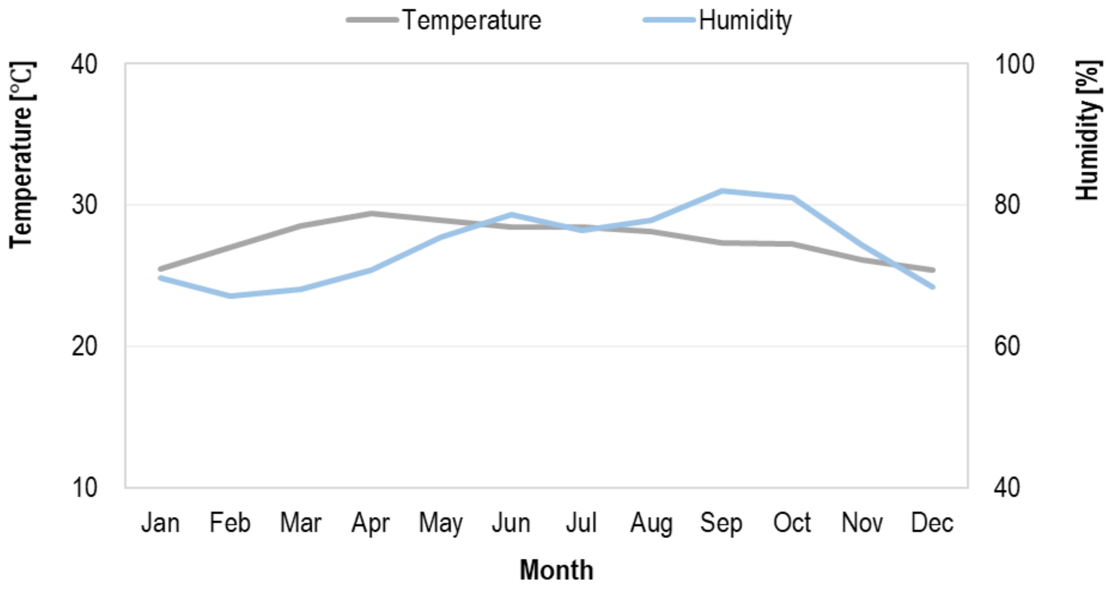


Figure 2.3 Average temperature and humidity in Thailand (Meteonorm, 2016)

Thailand has abundance of solar energy; the monthly average of global solar irradiation is 151 kWh/m^2 (Figure 2.4) (Meteonorm, 2016).

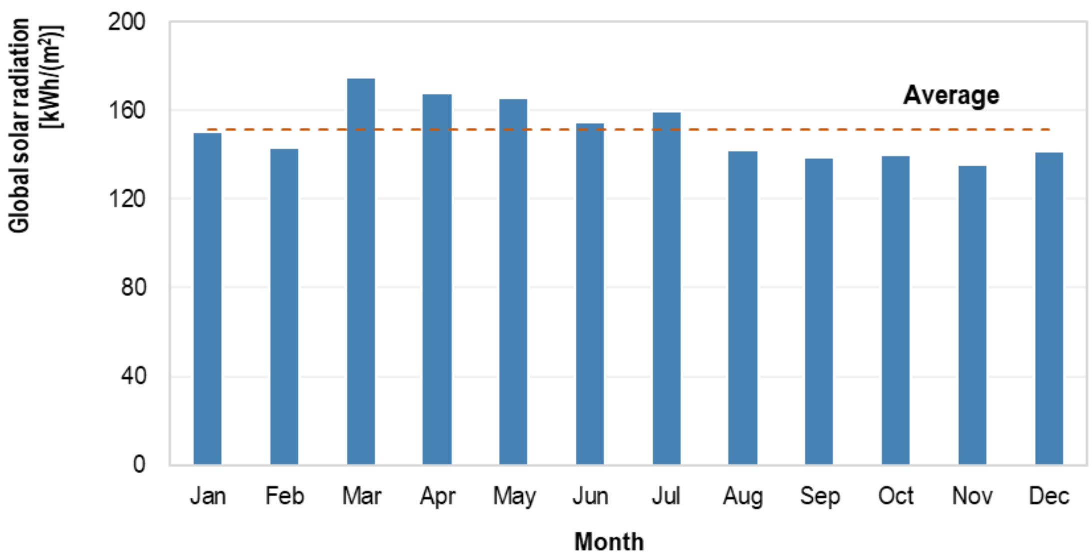


Figure 2.4 Global solar irradiation of Thailand by month (Meteonorm, 2016)

Thailand's yearly average global solar irradiation is approximately 1,812 kWh/m^2, while Germany has the average global irradiance of 1,055 kWh/m^2 (Figure 2.5) (The World Bank, 2019; Fraunhofer ISE, 2019).

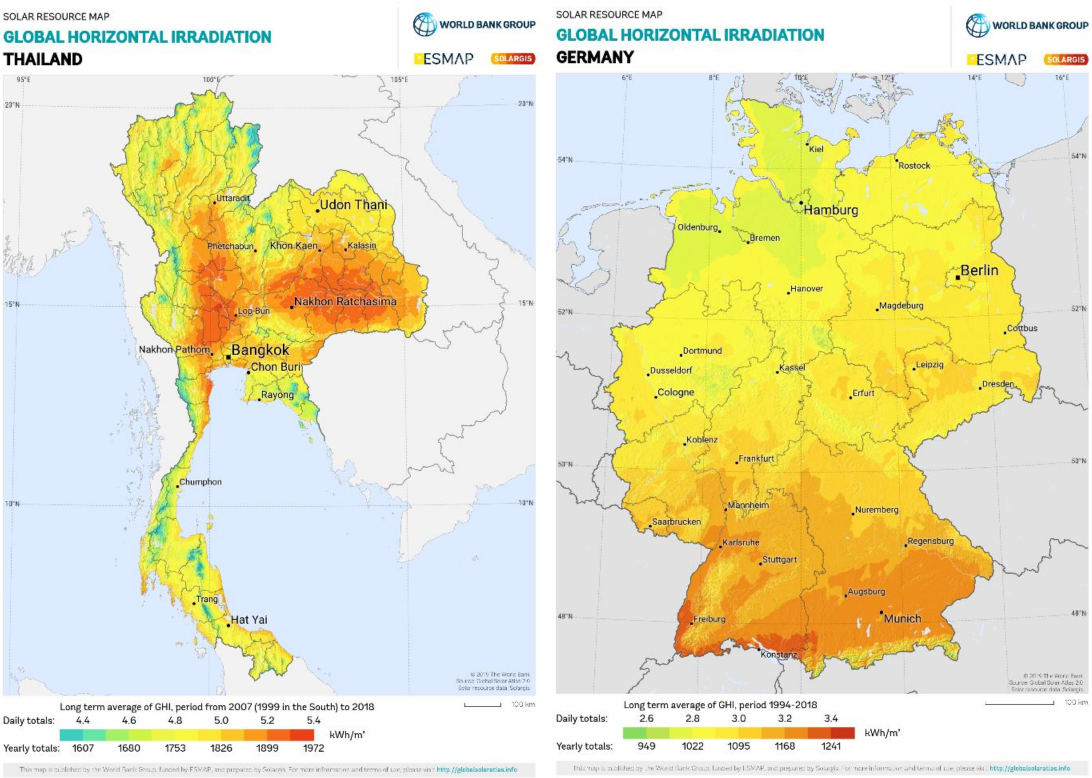


Figure 2.5 Global solar irradiation of Thailand and Germany (The World Bank, 2019)

2.3 Energy institutional structure and ownership

The tri-poly state-owned enterprise (SOE) has control over the electricity generation system, transmission system, distribution system, and retail services in Thailand (Figure 2.6) (Wisuttisak, 2010; EPPO, 2000; Wattana et al., 2008). The Electricity Generating Authority of Thailand (EGAT) is responsible for the electricity generation and transmission system, while the Provincial Electricity Authority (PEA) and the Metropolitan Electricity Authority (MEA) are the only two electric distributors/electricity retailers of the country.

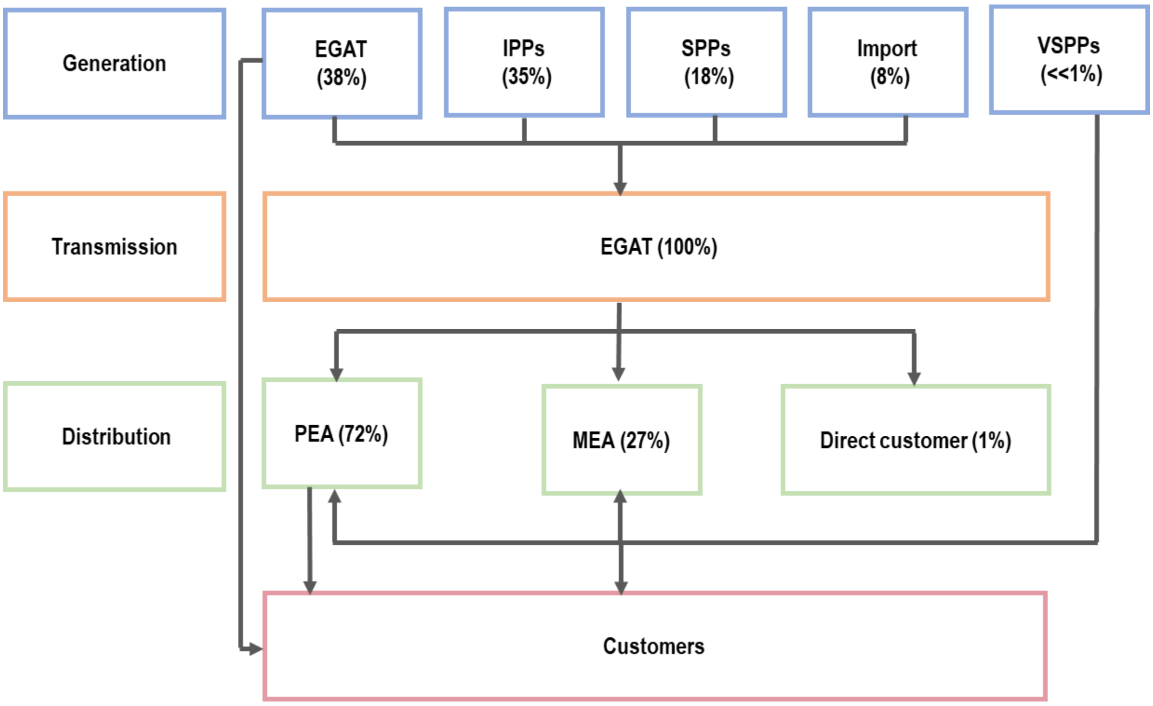


Figure 2.6 Electricity industry in Thailand (EPPO, 2017a)

The EGAT is under the Ministry of Energy's responsibility while the PEA and MEA fall under the Ministry of the Interior (Figure 2.7). The MEA is responsible for electricity distribution in Bangkok, Nonthaburi, and Samut Prakan provinces, while the PEA is responsible for the remaining provinces of the country. Obviously, Thai consumers have no other alternatives to buy electricity from other companies but only from the MEA and PEA, depending on the location.

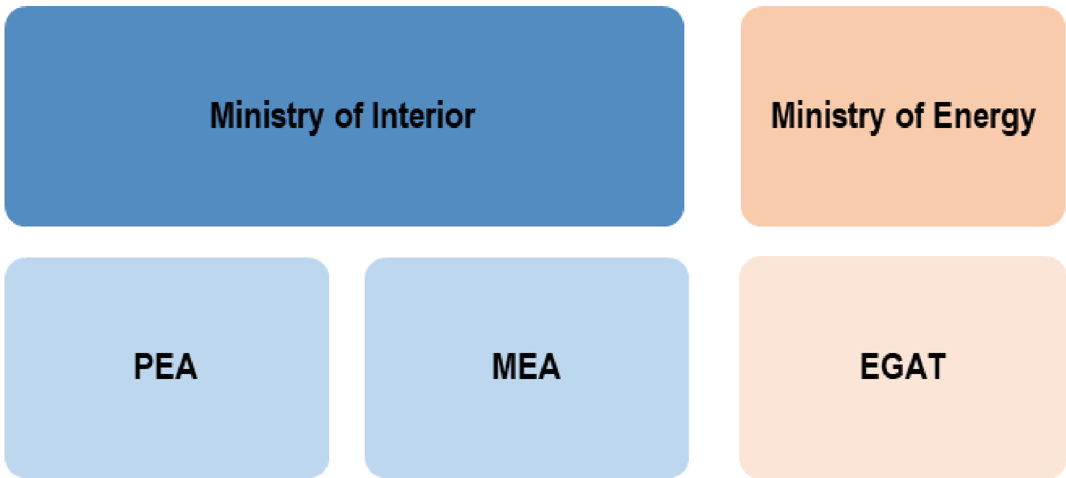


Figure 2.7 Electricity utility ownership (EPPO, 2017a)

In the past, the EGAT was the only electricity generator, but since 1992 the Thai government has introduced an independent power producer (IPP) to participate in the power sector. There was an attempt to restructure the electricity market structure from the tri-poly SOE to liberalization, but it was opposed due to the inappropriate regulatory framework and the apprehension of uncontrolled high electricity prices (Wisuttisak, 2010; Greacen, 2004).

The liberalization of the electricity market can boost up robust regional trade and heighten transparency (Connor et al., 2014; IEA, 2011). The possibility to restructure the Thai electricity market requires a strong policy signal from the government. Power market reform is very complex regarding the legal obstacles and strong opposition from the public concerning the price control mechanism, in particular.

2.4 Thailand's energy situation overview

2.4.1 Primary energy consumption

Thailand has limited primary energy resources. Imported energy has been increasing over the past ten years. The main energies imported are crude oil, which is consumed as petroleum products in the transportation sector and industry sector, followed by natural gas in the power sector. In 2017, the total primary energy consumption in Thailand was 134,228 kilotonnes of oil equivalent (ktoe) (1 ktoe = 41,868 GJ), of which imported primary energy accounted for 57% of the total primary energy supply (Figure 2.8). The average growth for primary energy consumption is approximately 2.8% per year (EPPO, 2017a; DEDE 2017).

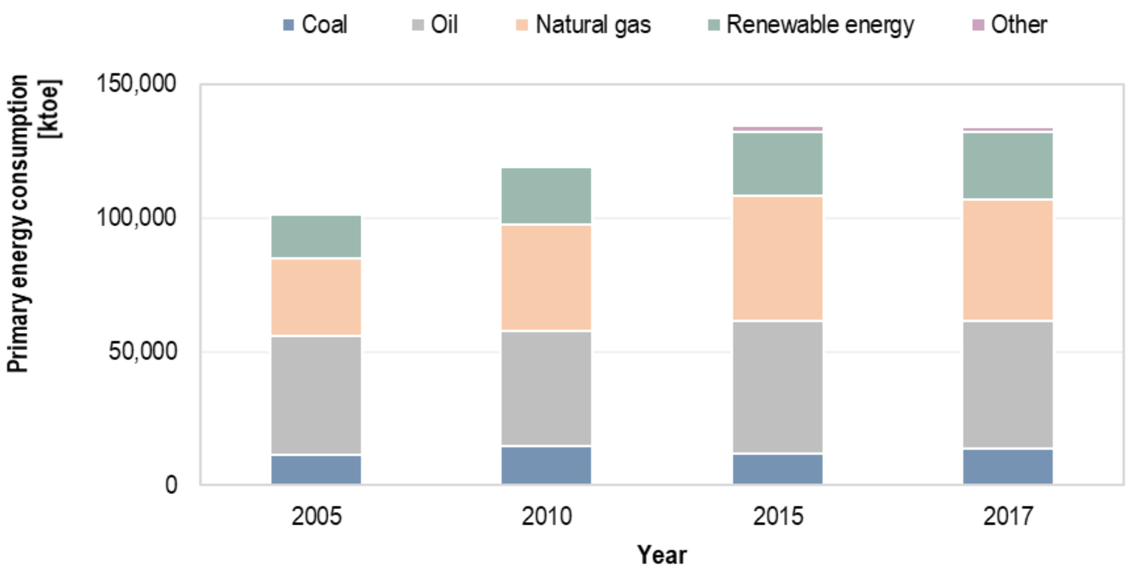


Figure 2.8 Primary energy consumption in Thailand by fuel types between 2005 and 2017 (EPPO, 2017a; DEDE 2017)

The transportation sector had the highest primary energy consumption at approximately 40%, followed by the manufacturing sector (35%), residential sector (13%), commercial sector (8%), and agriculture sector (3%) (Figure 2.9) (EPPO, 2017a; DEDE 2017).

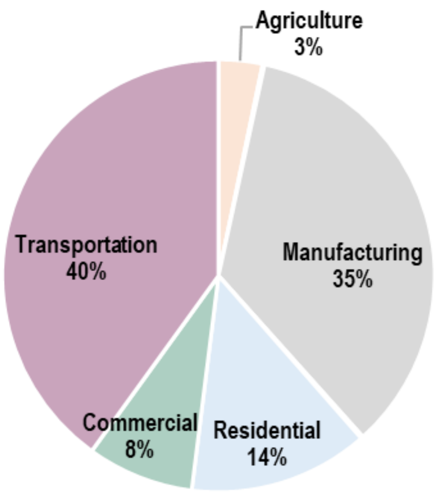


Figure 2.9 Primary energy consumption in Thailand by sector in 2017 (EPPO, 2017a; DEDE 2017)

2.4.2 Electricity consumption per capita

Thailand had electricity consumption of 2.8 MWh per person in 2017 while in Germany was 7 MWh per person. In other words, Germany had electricity consumption per capita 2.5 times higher than Thailand (Figure 2.10). The electricity consumption per capita of Thailand has been increasing over the past 10 years, whereas in Germany it has been almost constant.

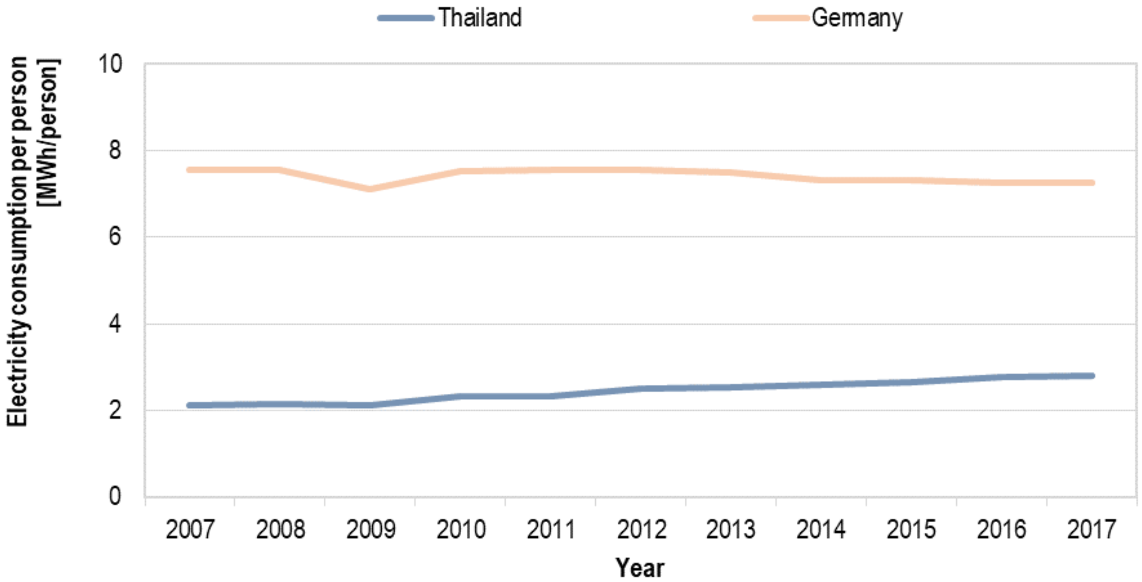


Figure 2.10 Electricity per capita in Thailand and Germany between 2007 and 2017
(EPPO, 2017a; BMWi, 2019)

2.5 CO_2 emissions

Environmental impact is one of the energy planning concerns for Thailand. Over the past ten years, CO_2 emissions have been increasing continuously due to the reliance on fossil fuels. The total CO_2 emission in 2017 was 257 million tonnes with the growth of 2.5% per year (Figure 2.11).

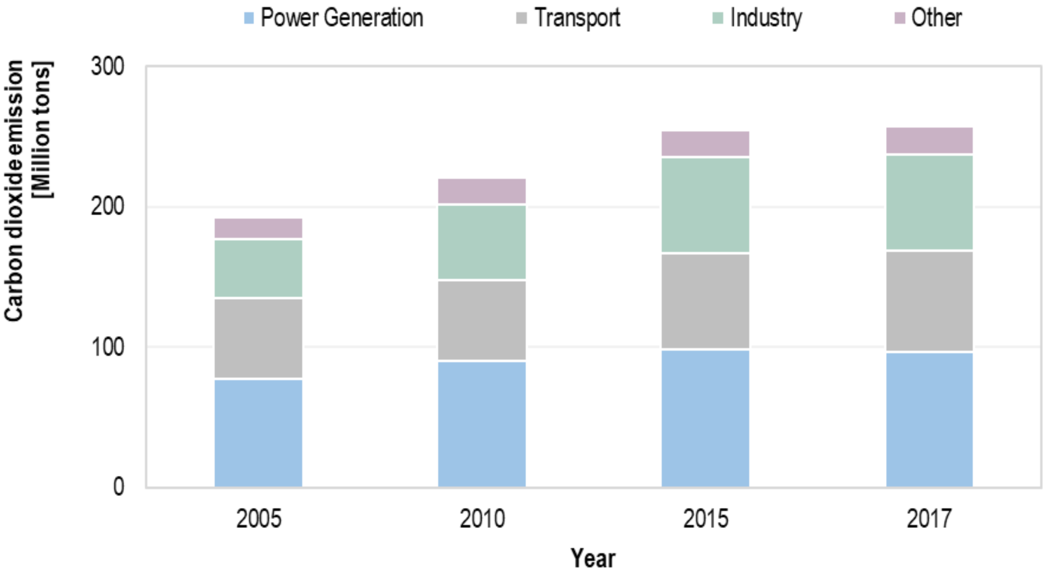


Figure 2.11 CO_2 emissions in Thailand by sector (EPPO, 2017a)

The CO_2 emissions per capita in Thailand was 3.9 tonnes of CO_2 per person while in Germany it was 9 tonnes of CO_2 per person (EPPO, 2017a; BMWi, 2019) (Figure 2.12).

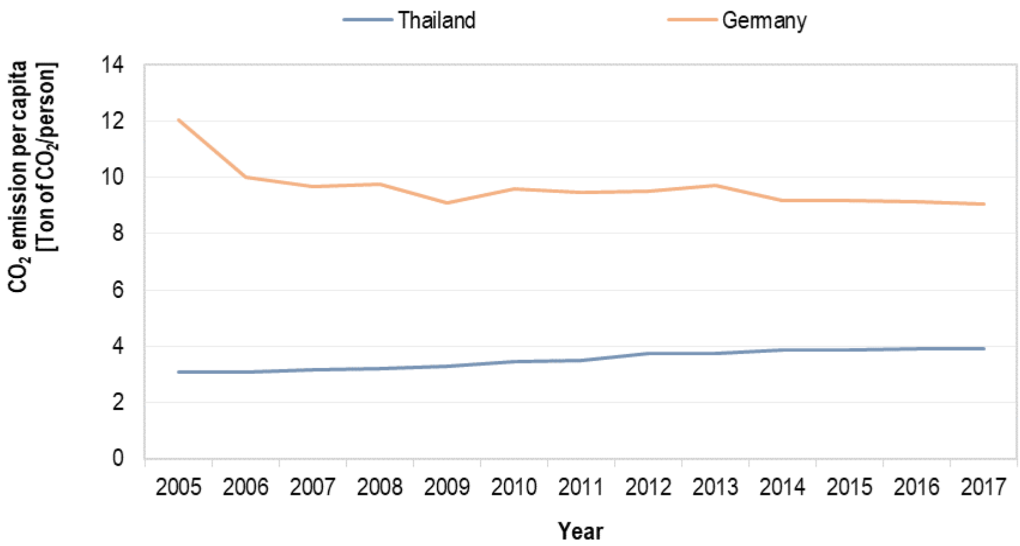


Figure 2.12 Comparison of CO_2 emissions per capita between Thailand and Germany (EPPO, 2017a; BMWi, 2019)

Germany has an ambitious target to reduce CO_2 emissions by at least 55% by 2030 compared with the year 1990 (BMU, 2018). The power generation sector is the main CO_2 producer in Thailand, which accounts for 37% of total CO_2 emissions, followed by industry (28%), transport (26%), and other (8%) (EPPO, 2017a; DEDE 2017). The power sector has excessive dependence on fossil fuels, especially natural gas and coal.

2.6 Energy policy in Thailand

Thailand has relied on fossil fuels to meet the energy demands of the country. The concerns of energy security and environmental issues have been challenges for future energy planning. Recently, the Thai government formulated a national energy integration plan named "Thailand Integrated Energy Blueprint (TIEB)", which focuses on three dimensions: security, economy, and ecology (MOE, 2015a). The national energy integration plan consists of five main energy plans (between 2015 to 2036):

1) Power Development Plan (PDP)
2) Energy Efficiency Plan (EEP)
3) Alternative Energy Development Plan (AEDP)
4) Gas Plan
5) Oil Plan

This research focuses on three energy plans related to the smart grid context: 1) the alternative energy development plan (AEDP), 2) the energy efficiency plan (EEP), and 3) the power development plan (PDP), which relate to the smart grid development.

2.6.1 Alternative Energy Development Plan (AEDP)

Renewable energy development in Thailand has grown continuously due to energy policy and incentive supports from the government. The Ministry of Energy has promoted renewable energy since 1989 by allowing the Electricity Generating Authority of Thailand (EGAT) to buy electricity from small power producers (SPP) who produce heat and electricity mainly from natural gas and some from municipal waste with a capacity between 10-90 MW. This can reduce the investment cost of the new fossil-fuel power plants and the CO_2 emissions in the power sector. Later on, the very small power producers (VSPP) participated in the power sector with a capacity of less than 10 MW.

In 2015, the Thai government established an alternative energy development plan (AEDP). The target of the AEDP is to achieve the renewable energy share by 30% of total final energy consumption in 2036 (MOE, 2015b) including electricity, thermal energy, and biofuel (Table 2.1).

Table 2.1 Renewable energy target of AEDP 2015 (MOE, 2015b)

Type	Unit	Year 2017	Target 2036
Solar	MW	2,698	6,000
Wind	MW	628	3,002
Small Hydro	MW	182	376
Biomass	MW	3,157	5,570
Biogas	MW	475	1,280
Municipal Solid Waste (MSW)	MW	191	550
Large Hydro	MW	2,906	2,906
Total	**MW**	**10,238**	**19,684**

In 2017, the total installed capacity from renewable energy in Thailand was 10,238 MW compared to Germany, which was 111,880 MW (BMWi, 2017). Biomass, solar power, and hydropower dominated renewable energy development with 86% of total installed capacity (Figure 2.13). According to the AEDP, the target of renewable energy in 2036 (19,684 MW) will be double of the renewable energy capacity in 2017. The proportion of renewable energy installed capacity in 2036 will be solar (30%), biomass (28%), wind (15%), large hydropower (15%), biogas (7%), MSW (3%), and small hydro (2%) (MOE, 2015b).

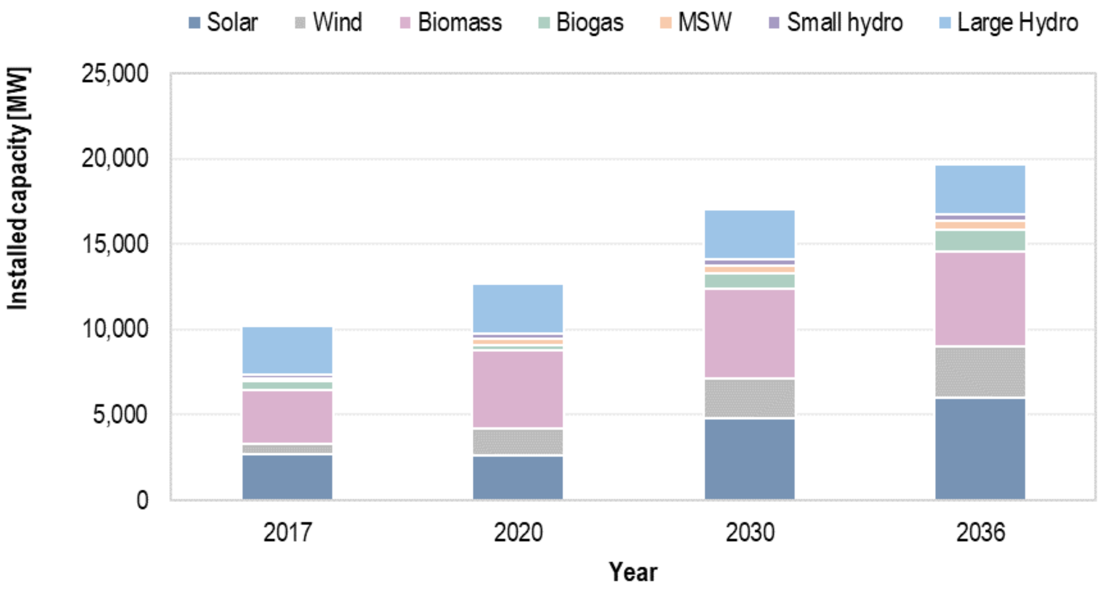


Figure 2.13 Installed capacity of renewable energy of AEDP (MOE, 2015b)

Thailand can reach the target easily because the current renewable energy installed capacity has already achieved more than 50% of its target according to the AEDP plan. Germany has set the renewable energy share of 50% and 65% of total electricity generation by 2030 and 2040, respectively (BMWi, 2018). Thailand aims to generate electricity from renewable energy at approximately 31% and 36% of total electricity generation by 2030 and 2036, respectively. The ambitious goal of renewable energy development in Thailand can be made by revising the renewable energy policy.

1) Feed-in premium or Adder program

Generally, the retail electricity price of Thailand consists of three elements, which are 1) the fuel price volatility adjustment tariff (Ft), 2) the base electricity price, and 3) VAT 7% (ERC, 2014). The historic retail electricity price for residential users in Thailand is shown in Figure 2.14 (ERC, 2017). The retail electricity price of Thailand is almost constant at 10 cents per kWh, while the retail electricity price in Germany has been increasing over the past ten years and reached 33 cents per kWh in 2017 (BMWi, 2019). The exchange rate 1 euro is equal to 40 baht in the Figure 2.14.

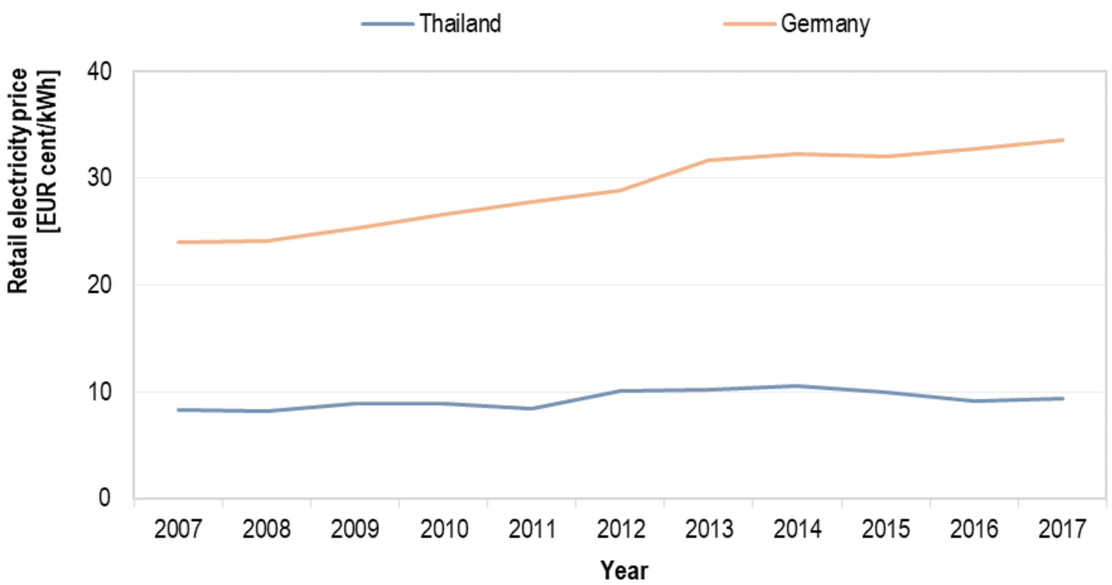


Figure 2.14 Retail electricity price in Thailand and Germany between 2011-2017 (ERC, 2017; BMWi, 2019)

The feed-in premium, or Adder program, was introduced in 2007 in order to attract renewable energy investors (Table 2.2). The Adder program was very successful because the incentive price was added on top of the retail electricity price and was granted for 7-10 years. The increase of fossil fuel directly affects the Ft rate in Thailand. In other words, the renewable energy investor also received the benefit through the increasing of the fossil fuel price without improving their performance and efficiency, while the price of the PV system has been decreasing continuously.

In 2017, the total PV installed capacity was 2,697 MW which consisted of 2,560 MW of ground-mounted PV and 137 MW of rooftop PV (DEDE, 2017) (Figure 2.15). In comparison, the PV installed capacity in Germany was 42,000 MW (Fraunhofer ISE, 2017). The Adder program is granted to the ground-mounted PV projects of 1,570 MW and the remaining 990 MW receives the FiT scheme. However, there is still power purchase agreement (PPA) under the Adder program in the pipeline that has to be transformed to the FiT scheme transition.

Table 2.2 Feed-in premium (Adder) rate for the renewable energy project in Thailand (ERC, 2009)

Type	Any province (EUR cent/kWh)	Three selected provinces (1) (EUR cent/kWh)	Area that uses diesel (EUR cent/kWh)	Time period (Years)
Biomass				
Capacity ≤ 1 MW	1.25	3.75	3.75	7
Capacity > 1 MW	0.75	3.25	3.25	
Biogas				
Capacity ≤ 1 MW	1.25	3.75	3.75	7
Capacity > 1 MW	0.75	3.25	3.25	
Hydropower				
50kW ≤ capacity ≤ 200 kW	2.00	4.50	4.50	7
Capacity < 50 kW	3.75	6.25	6.25	
Municipal Solid Waste				
Landfill	6.25	8.75	8.75	7
Thermal energy	8.75	11.25	11.25	
Wind				
Capacity ≤ 1 MW	11.25	15.00	15.00	10
Capacity > 1 MW	8.75	12.50	12.50	
Solar	20.00	23.75	23.75	10

(1) Projects in Yala, Pattani, Narathivat and 4 districts in Songkhla which are Chana, Thepha, Saba Yoi, and Na Thawi

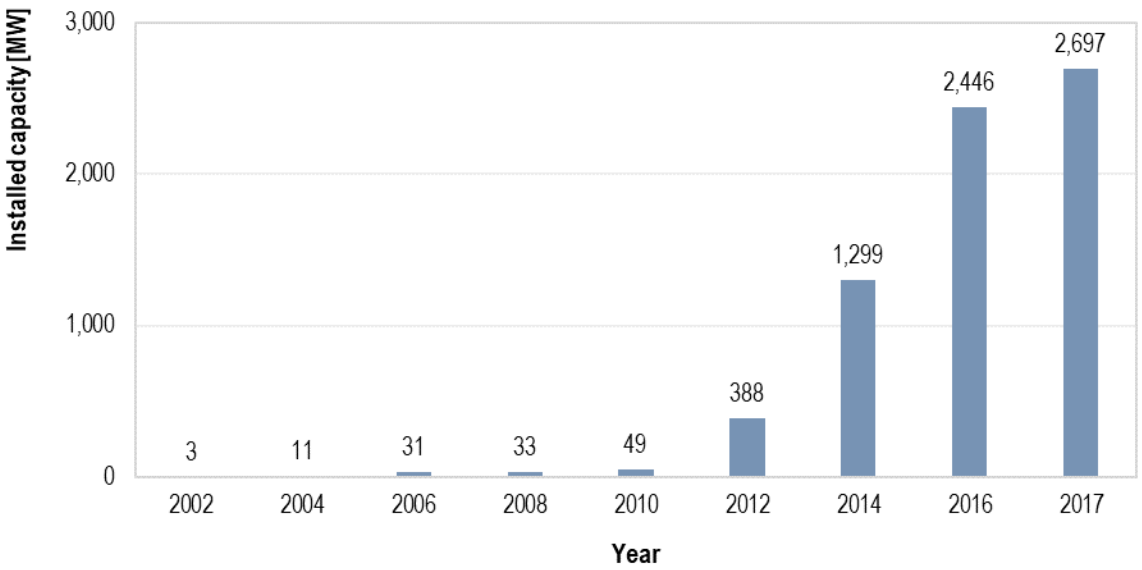


Figure 2.15 Installed capacity of PV in Thailand (DEDE, 2017)

The lack of regular reviews of the incentive rate and implementation time frame gave the unexpected speculative opportunity to the PV project investors. The investor can hold the PPA to gain more the benefit due to the increasing retail electricity price without the time frame limitation (IISD, 2013). Consequently, many PV projects were implemented in 2012, five years after receiving the PPA in 2007. The renewable energy investors received more profit without improving their efficiency nor increasing capacity from the defective Adder policy. Hence, the Thai government has canceled the Adder program and paused new PV investment until a new feed-in tariff scheme is in place.

2) Feed-in tariff

In 2014, the Thai government changed the Adder program to the feed-in tariff (FiT) system. (Table 2.3). The latest FiT rate has two components which are 1) fixed FiT (FiT_F), which is calculated from investment, operation and maintenance (O&M) costs, and 2) variable FiT (FiT_V), which is calculated from fuel cost. This FiT_V factor is applied to only bioenergy fuel (EPPO, 2015). The fixed payment is categorized by the type of renewable energy technology and its capacity. In addition, the FiT rate will be reviewed regularly (ERC, 2014).

Table 2.3 Feed-in tariff in Thailand (ERC, 2014)

Capacity	**FiT (EUR cent/kWh)**			**Time period (Years)**	**FiT (EUR cent/kWh)**	
	FiT_F	**FiT_V,**	**FiT (1)**		**Bioenergy (First 8 years)**	**Selected three provinces (2)**
1) MSW (Solid waste)						
Capacity ≤ 1 MW	7.83	8.03	15.85	20	1.75	1.25
Capacity > 1-3 MW	6.53	8.03	14.55	20	1.75	1.25
Capacity > 3 MW	5.98	6.73	12.70	20	1.75	1.25
2) MSW (Landfill)						
All capacity	14.00	-	14.00	10	-	1.25
3) Biomass						
Capacity ≤ 1 MW	7.83	5.53	13.35	20	1.25	1.25
Capacity > 1-3 MW	6.53	5.53	12.05	20	1.00	1.25
Capacity > 3 MW	5.98	4.63	10.60	20	0.75	1.25
4) Biogas (Wastewater)						
All capacity	9.40	-	9.40	20	1.25	1.25
5) Biogas (Food crops)						
All capacity	6.98	6.38	13.35	20	1.25	1.25
6) Hydro						
Capacity ≤ 200 kW	12.25	-	12.25	20	-	1.25
7) Wind						
All capacity	15.15	-	15.15	20	-	1.25

(1) FiT rate will increase according to core inflation
(2) Projects in Yala, Pattani, Narathivat and 4 districts in Songkhla which are Chana, Thepha, Saba Yoi, and Na Thawi

Table 2.3 Feed-in tariff in Thailand (Continued)

Capacity	FiT (EUR cent/kWh)			Time period (Years)	FiT (EUR cent/kWh)	
	FiT_F	FiT_V,	FiT (1)		Bioenergy (First 8 years)	Selected three provinces (2)
8) Solar						
0-10 kWp	16.73	-	17.40	20	-	1.25
> 10-250 kWp	16.38	-	16.38	20	-	1.25
> 250-1,000 kWp	15.40	-	15.40	20	-	1.25
Ground mounted	10.30	-	10.30	20	-	1.25

(1) FiT rate will increase according to core inflation
(2) Projects in Yala, Pattani, Narathivat and 4 districts in Songkhla which are Chana, Thepha, Saba Yoi, and Na Thawi

In comparison, Germany introduced the FiT in 2000 according to the first German Renewable Energy Sources Act, or Erneuerbare-Energien-Gesetz (EEG), to enhance renewable energy development in Germany (EEG, 2017). The FiT for renewable energy projects in Germany is shown in Table 2.4.

Table 2.4 Feed-in tariff in Germany (EEG, 2017)

Technology	FiT rate in 2017 (EUR cent/kWh)	Technology	FiT rate in 2017 (EUR cent/kWh)
Solar		**Biomass**	
Rooftop		Capacity ≤ 150 kWp	13.32
Capacity ≤ 10 kWp	12.70	Capacity ≤ 500 kWp	11.49
Capacity ≤ 40 kWp	12.36	Capacity ≤ 5 MWp	10.29
Capacity ≤ 750 kWp	11.09	Capacity ≤ 20 MWp	5.71
Ground Mounted			
Capacity ≤ 750 kWp	8.91	**Geothermal**	25.20
Wind		**Biogas**	
Onshore*	4.66-8.38	Landfill	
Offshore**	3.90-15.40	Capacity ≤ 500 kWp	8.17
		Capacity ≤ 5 MWp	5.66
Hydro		Sewage	
Capacity ≤ 500 kWp	12.40	Capacity ≤ 500 kWp	6.49
Capacity ≤ 2 MWp	8.17	Capacity ≤ 5 MWp	5.66
Capacity ≤ 5 MWP	6.25	Biowaste	
Capacity ≤ 10 MWp	5.48	Capacity ≤ 500 kWp	14.88
Capacity ≤ 20 MWp	5.29	Capacity≤ 20 MWp	13.05
Capacity ≤ 50 MWp	4.24	Manure	23.14
Capacity > 50 MWp	3.47		

Note: * depending on duration of payment
** depending on duration of payment and scheme chosen by plant operator

Since 2011, the new PV ground-mounted systems achieved grid parity and the new PV rooftops reached grid parity in 2012 in Germany (Figure 2.16). The FiT of the small PV system (less than 10 kWp) has decreased dramatically over the past ten years, from 50 cents per kWh in 2000 to 12.70 cents per kWh in 2017 (Fraunhofer ISE, 2019). The FiT for a small PV system is expected to drop further to fewer than 10 cents per kWh in 2020. According to the EEG 2017, a PV plant with a rated output of over 750 kWp is required to participate in the tender system and obligated for self-consumption. The PV system with a rated output of lower than 100 kWp still is eligible for a fixed FiT (EEG, 2017).

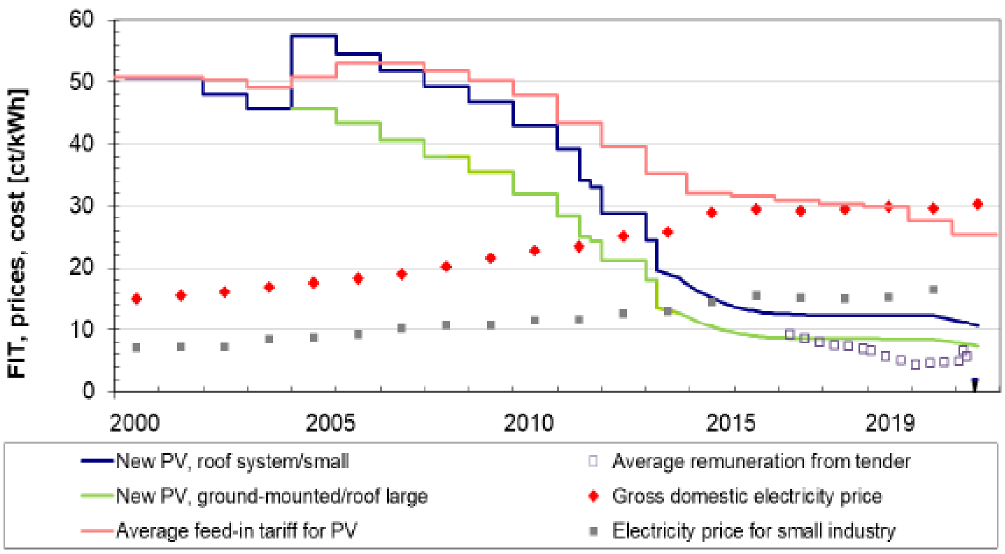


Figure 2.16 Feed-in tariff for PV system in Germany between 2000-2019 (Fraunhofer ISE, 2019)

3) Small power producer (SPP) hybrid and very small power producer (VSPP) semi-hybrid program

The variable renewable energy (VRE) produces intermittent electricity depending on season and geology. In order to promote the VRE as the firm energy resource, the Ministry of Energy (MOE) of Thailand has announced the latest renewable energy program in 2017, called “SPP hybrid firm and VSPP semi-hybrid”. The SPP hybrid firm program (10-50 MW) offers the PPA from a mix of renewable energy technologies combined with/without energy storage systems. The VSPP semi-hybrid program (< 10MW) allows only one type of renewable energy, from either biogas or biomass with and without energy storage system combination (Table 2.5).

Table 2.5 Feed-in tariff for SPP hybrid firm and VSPP semi hybrid firm (EPPO, 2017b)

Capacity	**FiT (EUR cent/kWh)**			**Time period (Years)**	**FiT (EUR cent/kWh)**	
	FiT_F	**$FiT_{V,}$**	**FiT (1)**		**Bioenergy (First 8 years)**	**Selected three provinces (2)**
1) SPP Hybrid Firm						
Capacity > 10-50 MW	4.53	4.63	9.15	20	-	-
2) VSPP Semi Firm						
Biomass						
Capacity ≤ 3 MW	6.53	5.53	12.05	20	1.00	1.25
Capacity > 3 MW	5.98	4.63	10.60	20	0.75	1.25
Biogas						
Sewage/waste	9.40	-	9.40	20	1.25	1.25
Energy crops	6.98	6.38	13.35	20	1.25	1.25

(1) FiT rate will increase according to core inflation
(2) Projects in Yala, Pattani, Narathivat and 4 districts in Songkhla which are Chana, Thepha, Saba Yoi, and Na Thawi

The SPP hybrid must commit as a firm contract to supply power during peak and off-peak, while the VSPP semi-hybrid only firmly commits for six months of the year, which must cover the summer season from March until June (EPPO, 2017b). The quota of SPP hybrid firm is 300 MW while the VSPP semi-hybrid firm is 268 MW depending on the location. The FiT rate under the SPP and VSPP hybrid scheme will be revised regularly to reflect the real investment cost.

2.6.2 Energy Efficiency Plan (EEP)

The Thai government foresees the increasing of fuel price and the climate change problem, which affects the economic competitiveness and welfare of people in the country. In 2011, the Thai government committed with the Asia Pacific Economic Cooperation (APEC) to promote energy conservation, energy efficiency, and reduce energy intensity. Therefore, the national energy efficiency plan (EEP) was established by the Ministry of Energy in 2015 as a long-term implementation plan until 2036 (MOE, 2015c).

The EEP 2015 has set the target to reduce energy intensity by 30% in 2036 compared to the reference year 2010, or equivalent to the final energy consumption reduction of 56,142 ktoe. Thailand has been implementing the energy efficiency measures since before the EEP 2015 plan. The accumulative energy saving was 4,442 ktoe and the energy saving during the EEP 2015 is expected to be 51,700 ktoe. As a result, the expected final energy consumption reduction according to the EEP 2015 is 56,142 ktoe (Figure 2.17).

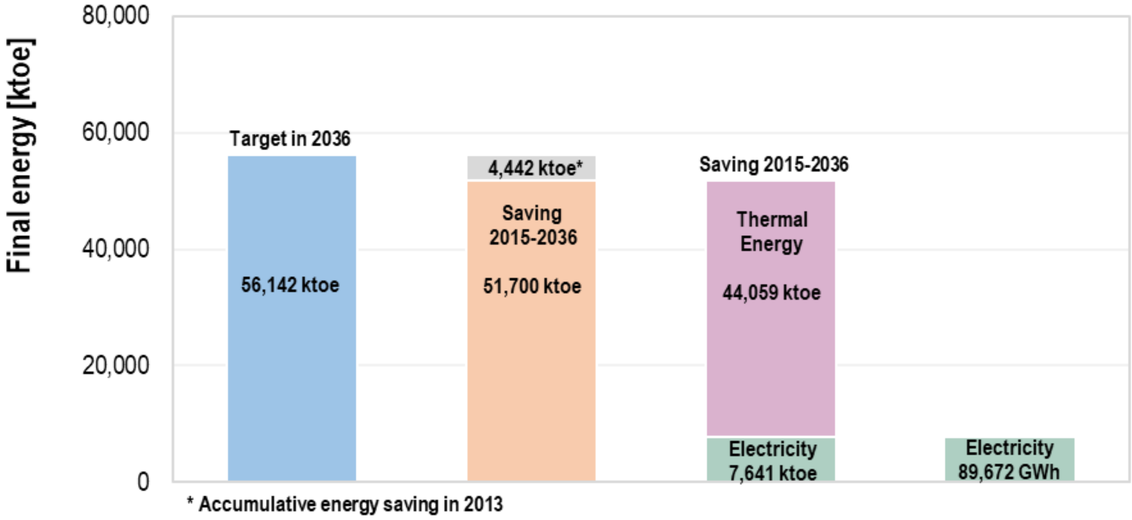


Figure 2.17 Energy saving potential under the EEP 2015 (MOE, 2015c)

There are three main strategies to achieve the energy intensity target: the compulsory program, voluntary program, and complementary program. By the end of 2036, the expected electricity saving of 86,672 GWh is categorized into four sectors: commercial building (41%), industry (36%), residential (15%), and government building (8%) (Figure 2.18). There are six main measures for electricity saving under the EEP 2015:

1) Specific Energy Consumption (SEC)
2) Building Energy Code (BEC)
3) High Energy Performance Standard (HEPs) and Minimum Energy Performance Standard (MEPs)
4) Monetary Incentive
5) Light-Emitting Diode lamp (LED) promotion
6) Energy Efficiency Resource Standard (EERS)

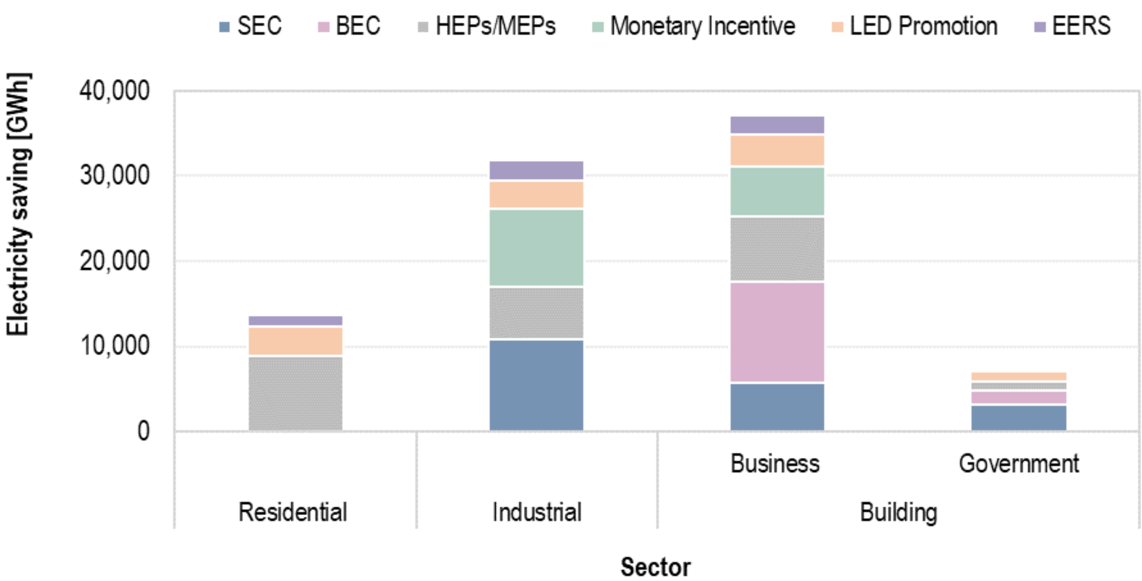


Figure 2.18 Electricity saving under the EEP 2015 by sector (MOE, 2015c)

It can be seen that business building is expected to be the main contributor for energy saving under the EEP 2015 through the BEC measure, while the SEC measure will play a significant role for energy saving in the industrial sector. The energy efficiency implementation in the residential sector focuses on energy labeling through MEPs and HEPs (e.g. electric appliances), EERS, and LED deployment. According to the EEP 2015, the BEC measure is not considered for the implementation in the residential sector. The EERS is a measure similar to the renewable energy standard (RES), in which the electric utility must implement the efficiency measures to the end user to meet the energy saving target (NREL, 2014).

2.6.3 Power Development Plan (PDP)

Thai power generation has been dominated by natural gas. In 2017, the total electricity generation was 201,166 GWh, which consisted of natural gas (60%), coal (18%), imported (12%), renewable energy (7%), and others (3%) (EPPO, 2017a) (Figure 2.19). The total installed capacity in Thailand was 42 GW in 2017, while the installed capacity in Germany was 203 GW. The main installed capacity of Thailand is based on natural gas at approximately 50% of the total installed capacity, whereas the majority of power plants in Germany are based on renewable energy, which is more than 54% of total installed capacity (Fraunhofer ISE, 2017).

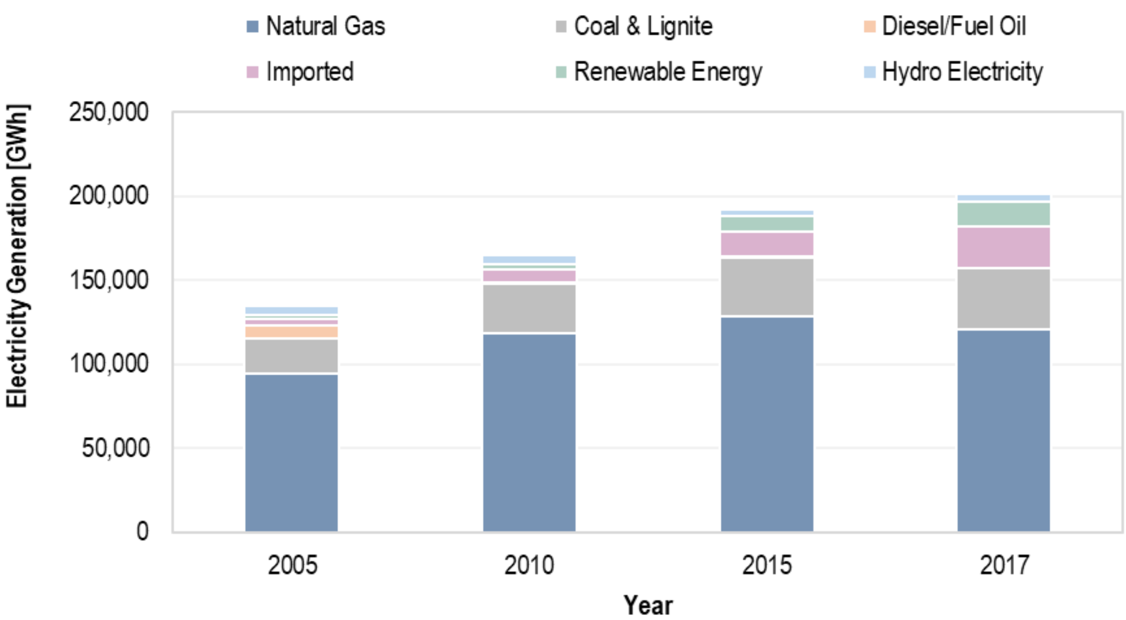


Figure 2.19 Electricity generation in Thailand by fuel type between 2005 and 2017 (EPPO, 2017a)

Increasing fuel diversification was the main objective in the Power Development Plan in 2015 (PDP 2015) by the Electricity Generating Authority of Thailand (EGAT) and Energy Policy and Planning Office (EPPO), by increasing the renewable energy share and imported electricity from neighboring countries. Moreover, the PDP 2015 aims to deploy 2,000 MW of nuclear power by 2036 (Figure 2.20). The significant change in this PDP plan is the full potential integration from the AEDP and the EEP. This is to increase the fuel diversification for electricity generation and reduce CO_2 emissions (MOE, 2015d).

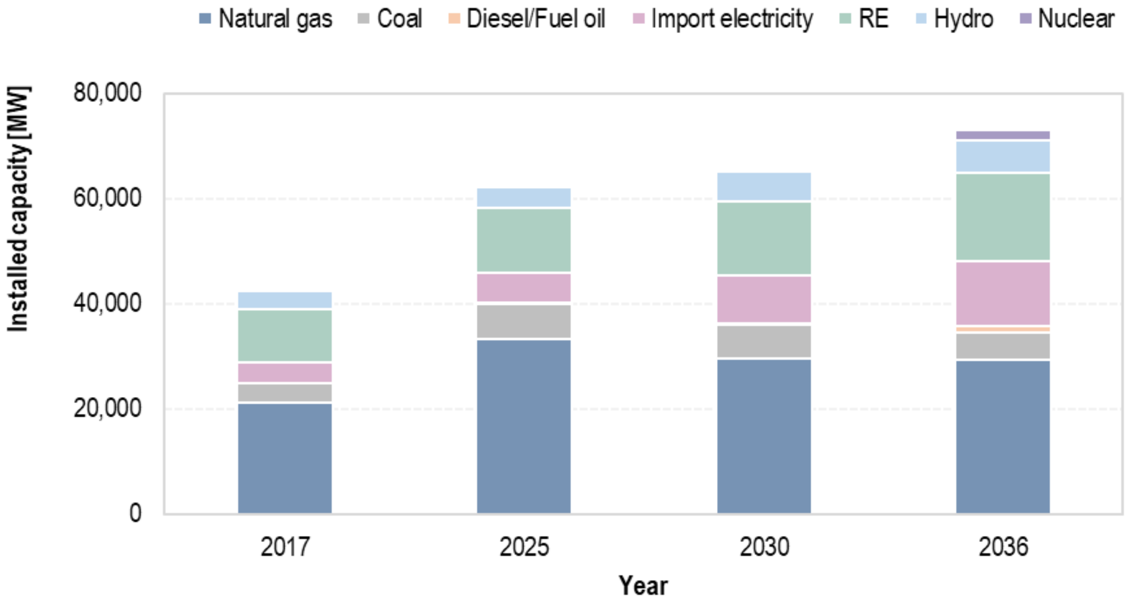


Figure 2.20 Installed capacity of Thailand according to the PDP 2015 (MOE, 2015d)

By 2036, Thai power generation will reduce the natural gas share from 60% to 40% of total electricity generation. On the other hand, the renewable energy proportion will increase from 7% to 30% of total electricity generation. Imported electricity from neighboring countries, especially from Laos, will increase up to 17% of total electricity generation. In 2017, CO_2 emissions per kWh of the power generation in Thailand was 477 grams of CO_2/kWh, which was close to Germany's power generation of 461 grams of CO_2/kWh (Figure 2.21). The reduction of fossil fuel and increasing of renewable energy will reduce the CO_2 emissions in power generation from 477 to 300 grams of CO_2/kWh by 2036.

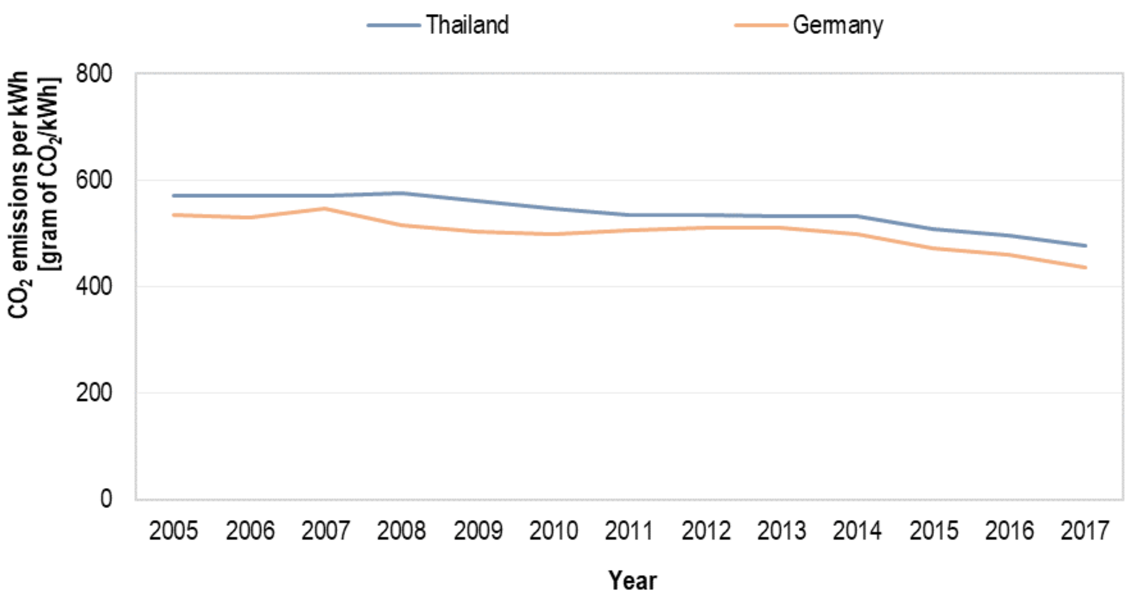


Figure 2.21 CO_2 emissions in power generation of Thailand and Germany between 2005 and 2017 (EPPO, 2017a; Fraunhofer ISE, 2017)

The total installed capacity and electricity consumption under the PDP 2015 are formulated from the adjustment GDP growth and include all energy efficiency measures according to the EEP 2015. This results in the reduction of peak demand and reserve power plants. By 2036, the peak demand is expected to be 49,655 MW with the load factor at approximately 67.89% (Figure 2.22). The total installed capacity and its total electricity generation will be 73,145 MW by the end of 2036.

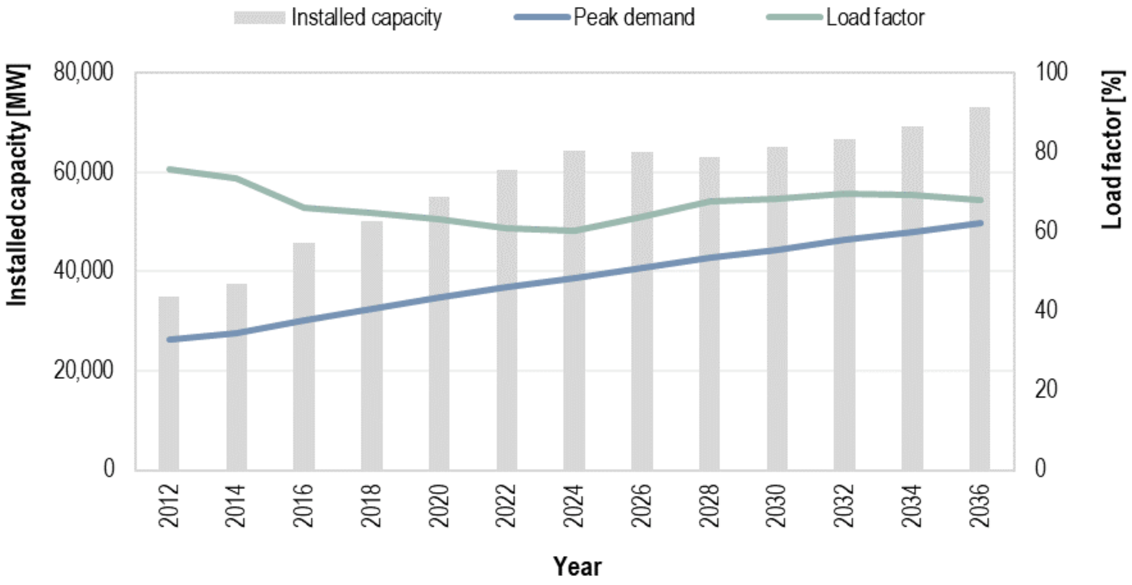


Figure 2.22 Installed capacity, peak demand, and load factor in PDP 2015 (MOE, 2015d)

Natural gas is still dominating Thai power generation. The attempt to deploy coal and nuclear power plants is facing public opposition regarding the environmental impact from the coal power plant and the safety of the nuclear power plant. It should be remarked that the installed capacity of renewable energy of the latest PDP 2015 is greater than any previous PDP plans in the past. The Thai government should aspire to increase the share of renewable energy in the power sector as it is a domestic resource and is environmentally friendly. Observing the electric grid impact from the early state of renewable energy adoption would benefit long-term energy planning with the smart grid technology adoption.

2.7 Conclusion

Thailand has been relying on fossil fuels for economic development. However, the domestic primary energy reserve is limited, which results in higher imported energy from abroad for consumption in the power sector and the transportation sector. The reliance of high fossil fuel has raised the environmental impacts for future energy system planning in Thailand. Consequently, the Thai government has established the Integrated Energy Blueprint (TIEB), combining five major national energy development plans such the oil plan, gas, Power Development Plan (PDP), Alternative Energy Development Plan (AEDP), and Energy Efficiency Plan (EEP). The AEDP, EEP, and PDP plans are three main energy policies, which are related to the smart grid development because it is related to the electricity system.

According to the AEDP, Thailand will have a renewable energy share at approximately 30% of total final energy consumption by 2036. Currently, the renewable energy (RE) share has reached more than 50% of its target. The RE target can be more ambitious to achieve a decarbonization energy system. The feed-in tariff (FiT) is the only incentive scheme available for the RE development in Thailand where net metering and net billing programs are still absent. The EEP 2015 is one of the main energy policies to reduce energy intensity by 30% in 2036 or equivalent to the final energy consumption reduction of 56,142 ktoe. The commercial building and industrial sectors are expected to be two main focuses for reducing electricity consumption through specific energy performance and building energy code measures. Unfortunately, the existing building energy code of Thailand is not considered for residential building under the EEP action plan.

The Power Development Plan (PDP) 2015 was the first power development plan that integrated the full potential of renewable energy and energy efficiency. Accordingly, the share of renewable energy is more aggressive than that of previous PDP plans in the past. However, natural gas will still dominate power generation but only 40% of total electricity consumption in 2036. Renewable energy will play a more important role in the power sector by contributing 30% of total electricity generation, which is mainly from solar energy and biomass. The ground mount PV project will continue to dominate the solar energy target. Neither the AEDP 2015 nor the PDP 2015 have clear clarification for the rooftop PV contribution to the future energy system.

The main energy policies of Thailand do not commit strong action toward the Paris Agreement by limiting global warming to well below 2 ^{o}C (UN, 2015). Thailand can put its best effort to pursue the climate change target by integrating its full potential, both in energy efficiency and renewable energy, into action. The large renewable energy investors have the advantage of financial affordability to invest in additional infrastructure (e.g. cable, transformer, protection equipment) to meet the distribution system operator requirements, while the small players are still facing aged technical requirements in the low voltage network (e.g. limiting PV capacity by the transformer capacity). The smart grid would enable the small players in the system with advanced technology implications for effective management and control. However, this requires a strong energy policy to increase the competitiveness of the small players under fair regulations.

- empty page -

Chapter 3

Smart Grid Literature Review

3.1 Introduction

Renewable energy has become an attractive solution for future energy system planning because it is environmentally friendly. However, some existing networks may have a limitation on handling a large amount of the variable renewable energy. Fortunately, smart grid technologies can overcome constraints by providing advanced information communication technology (ICT) features to manage energy demand and supply efficiently. Smart grid deployment is very broad in different contexts regarding energy policy and country roadmaps. Several studies have indicated that non-technical issues, such as privacy issues, consumer behavior awareness, and institutional problems, have become just as crucial for smart grid development as the technical ones.

This chapter presents the literature review on state-of-the-art smart grid technology implications in the electrical system at the end user. Moreover, it also presents the mainstream of smart grid roadmaps in the EU, USA, and Thailand, which were first initiated by the electric utilities. The lessons learned of smart grid development in both technical and non-technical aspects from other countries can provide an insightful guideline for readers in which the context of technology implications can be applied to the end-user in the case of Thailand.

3.2 Definition of smart grid

What is a smart grid? The word “smart” is often asked with what is the difference between a normal grid and a smart grid. There are several definitions of a smart grid, depending on the area of focus. The term smart grid was proposed by the Electric Power Research Institute (EPRI) in 2002, which was defined as “a new type of highly integrated power grid, the combination of modern advance sensing and measurement technology, information technology, communication technology, control technology and physical power system” (Yuan et al., 2014). The early definition of smart grid development mainly focused on technology in electrical systems to enhance the reliable operation of the system (Blumsack & Fernandez, 2012).

The traditional consumer under the typical electrical grid is forced to be a non-active consumer, but they have the potential to be involved in decision-making in responsive price signals and behavior changes through ICT technologies (Torriti et al., 2010). The smart meter symbolizes the communication pathway between the consumer and electric utility. The traditional consumer can become the proactive consumer or, even better, as the prosumer. The European technology platform introduced the consumer dimension into the smart grid definition as an “electricity network that can intelligently integrate the behavior and actions of all users connected to it such as generators, consumers, and those that do both, in order to efficiently deliver sustainable, economic and secure electricity supplies” (Connor et al., 2014).

In short, the smart grid can be referred to as an energy system transition from centralized to decentralized, from traditional consumer to proactive consumer and prosumer, and from one-way communication to two-way communication by using the ICT technologies (Figure 3.1).

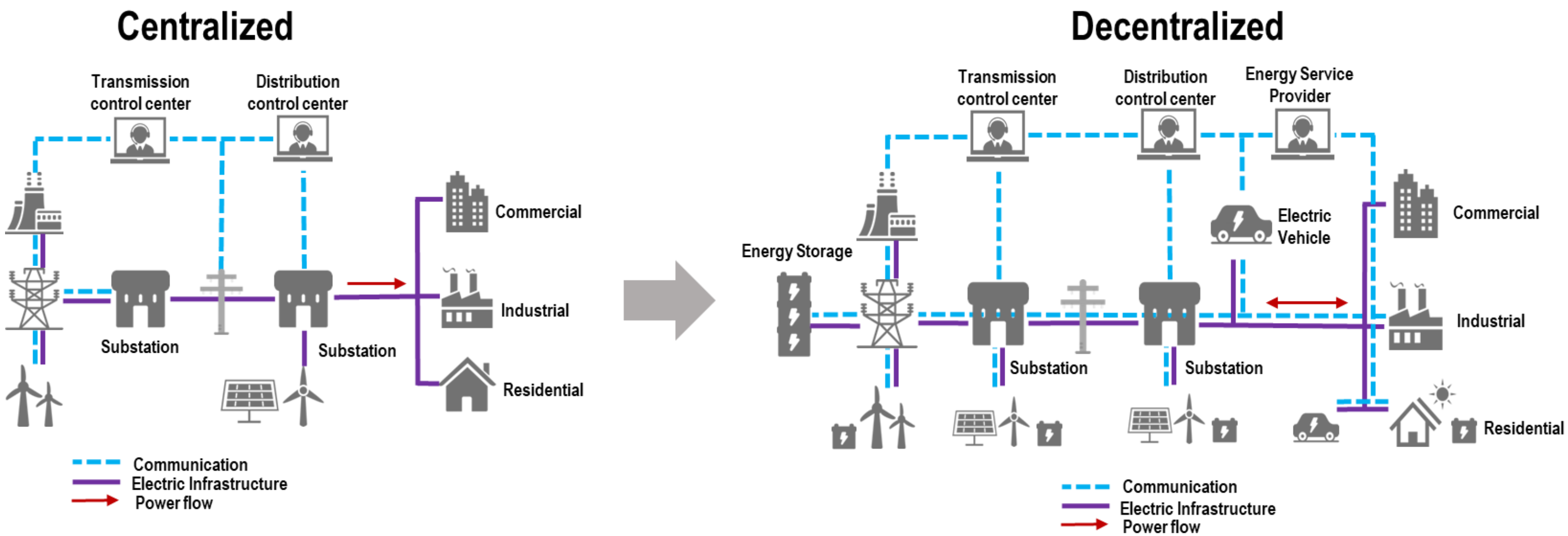


Figure 3.1 Electricity system transition from centralized to decentralized

3.3 Smart grid architecture model (SGAM)

The smart grid architecture model (SGAM) was established under the M/490 EU mandate for the standardization of the smart grid. The SGAM was developed by the European Commission (EC) with the European standardization bodies CEN (Comité Européen de Normalisation), CENELEC (European Committee for Electrotechnical Standardization), and ETSI (European Telecommunications Standards Institute). The SGAM framework offers the design of smart grid system use cases which can be used as a viewpoint for communication between stakeholders. The SGAM consists of three dimensions, which are domain, zone, and interoperability (CEN-CENELEC-ETSI, 2012) (Figure 3.2).

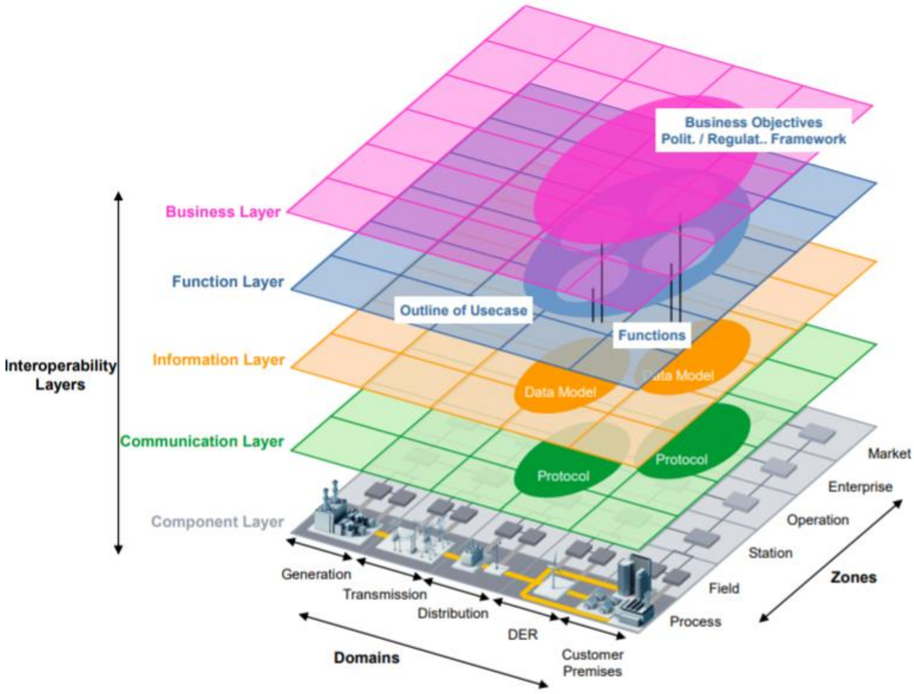


Figure 3.2 SGAM framework interoperability (CEN-CENELEC-ETSI, 2012)

3.4 Smart grid technology in the electrical system

According to the SGAM framework, smart grid technologies can be categorized into five domains, which are generation, transmission, distribution, distributed energy resource (DER), and customer premises or end user. Smart grid technology offers holistic solutions for the existing electricity network to become an intelligent electric grid network by integrating the ICT. A wide range of smart grid technology has been deployed on the commercial scale as shown in Table 3.1 .

Smart grid technology enables sophisticated electric system management such as balancing load, fault and loss detection, real-time wide range monitoring, data management, and enabling demand response. The Advanced Metering Infrastructure (AMI), or smart meter, is widespread smart grid technology for the end user which provides automatic real-time reading, demand-side management, and demand response programs. The smart meter with data access channels allows information flow between the end-user and the electricity provider, which emerges as the new energy service and business models for the electric utility companies.

Table 3.1 Smart grid technology in the electricity system

Domain in electric system	Smart grid technology
Generation	• Generation management system
Transmission	• Wide Area Protection and Control (WAPC) • Wide Area Monitoring System (WAMS) • Wide Area Situation Awareness (WASA) • Supervisory Control and Data Acquisition (SCADA) • Self-healing automation system • Fault location system • Flexible AC Transmission Systems (FACTS) • Dynamic Line Ratings (DLR) • Real Time Thermal Rating (RTTR)
Distribution	• Geographic Information Systems (GIS) • Distribution Management System (DMS) • Outage Management System (OMS) • Workforce Management System (WMS) • Network Management System (NMS) • Mobile Workforce Management System (MWMS) • Supervisory Control and Data Acquisition (SCADA) • Distribution Management System (DMS) • Feeder automation system • Substation automation system
Distributed energy resource (DER)	• Energy Management System (EMS) • Distributed energy resource operation • Virtual power plant (VPP)
Customer premise	• Advance Metering Infrastructure (AMI) • Metering-related back office system • Meter Data Management System (MDMS) • Web portal user interface • Demand side management system • Demand response management system • Electric vehicle (EV) • Energy storage system • Smart electric appliance with sensors and automation systems

3.5 Smart grid applications at the end user

The smart grid is not limited only to the electrical system but also empowers the consumer to be a proactive consumer and prosumer with integrated technologies. The proactive consumer learns to manage their energy demand to lower their energy costs with the price signal. The prosumer has begun to generate electricity and store it in the energy storage system or by charging an electric vehicle. Ancillary services can be found from the end user with integrated technologies to the electricity network by sending the signal through ICT features.

This section illustrates the example of smart grid applications at the end user which have been deployed in the smart grid context. There is no solid format in which technologies must be implemented, but rather depending on its specific technology characteristic that can contribute energy services to the smart grid development.

3.5.1 Building as the power plant

A building can perform as a power plant in the smart grid. The building with only a home automation system is not considered as a smart building in the smart grid perspective due to the fact that it does not contribute any energy services to the electricity network. The smart building in the smart grid refers to the sustainable building which consumes low energy, generates energy, and manages energy efficiently.

The smart residential building in practice is a combination of an integrated energy design concepts to reduce the energy demand and maximize the use of renewable energy, as shown in

Figure 3.3. As can be seen, the building is equipped with the PV system to provide the energy demand in the building. The battery system enhances the PV self-consumption in the building and reduces reversed power flow to the electricity grid network during a mismatch of energy demand and supply. Energy design in the building is essential as it can provide a wide range of energy services to the electricity network by selecting the proper technologies (Fisch et al., 2013).

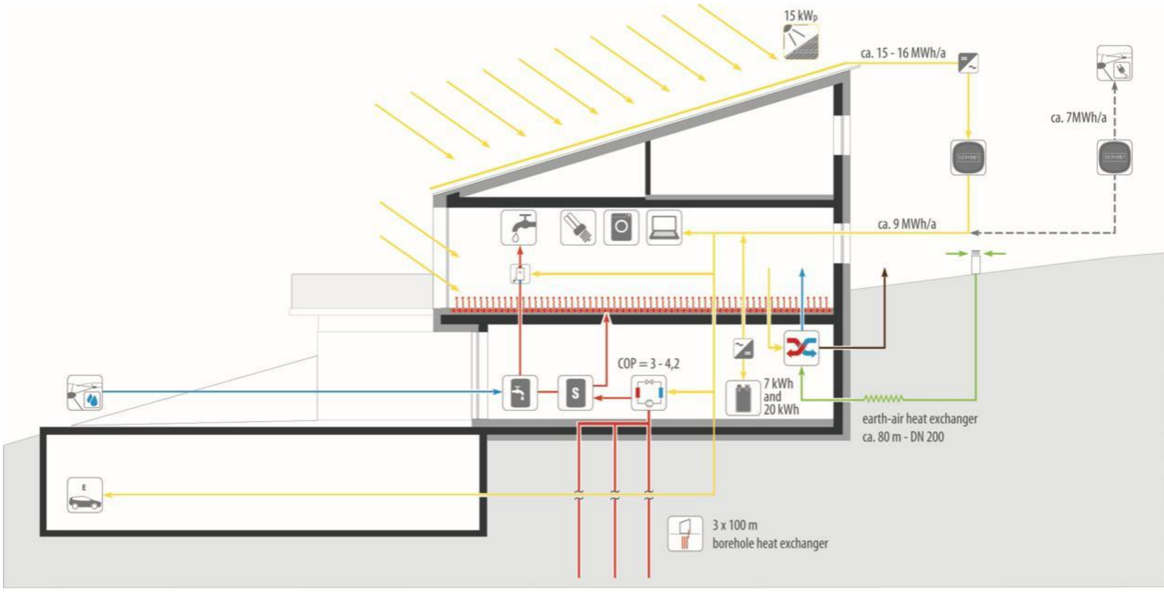


Figure 3.3 Residential EnergyPLUS building (Fisch et al., 2013)

3.5.2 Energy storage system (ESS)

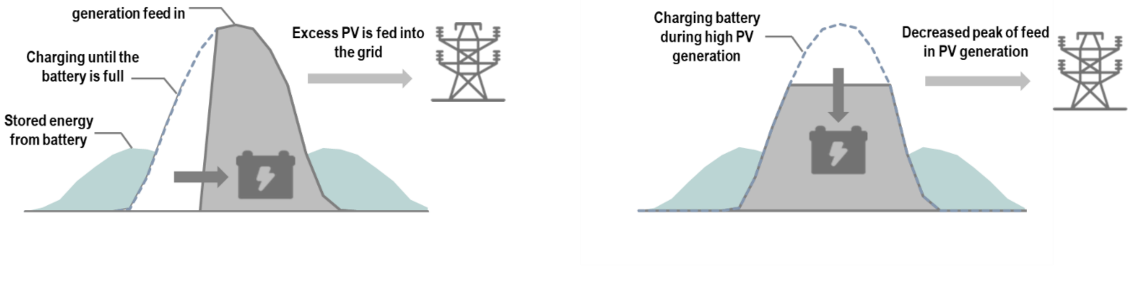
Variable renewable energy (VRE), such as wind and solar energy, have intermittent production depending on the location and the weather. The mismatch of high-energy generation from the VRE and the energy demand in a residential building increases the challenges for the distribution system operator (DSO) for power quality control. The energy storage system (ESS) can lessen the problem by storing excess energy and providing energy when demand occurs. The ESS can be deployed in various applications in both electricity and thermal energy. The battery energy storage (BES) system is the most widespread application to store electricity and interact with the electricity grid network, whereas the thermal energy storage system (TES) provides useful energy in the form of heating and cooling energy to the end user (IEA, 2014b). The ESS system applications at the end users in the smart grid context are given below.

3.5.2.1 Battery energy storage (BES) applications

The battery energy storage (BES) applications can be seen in on-grid and off-grid systems. The off-grid application is commonly used in remote areas and islands where there is lack of accessibility for the transmission line. The on-grid system usually interacts with the electricity network by storing electricity during low electricity prices or high excess energy from the renewable resource and then delivering electricity when the demand occurs or at high electricity prices.

Optimizing control for the BES with the price signal can help the consumer save energy costs (Schreiber & Hochloff, 2013). The main advantage for the BES utilization is increasing PV self-consumption up to 13-24% (Luthander et al., 2015). However, the high investment cost of the BES is the main barrier, especially in the residential sector in developing countries. In Germany, the KfW bank enhances the PV self-consumption by providing low-interest loans for energy storage system investment to the PV owners (EC, 2015a).

The BES application deployment can contribute ancillary service to the distribution system operator (DSO) by integrating a charging and discharging control strategy. The optimizing control strategy can increase self-consumption and, at the same time, decrease the amount of excess electricity fed back to the grid (IRENA, 2015; Alam, 2013) (Figure 3.4). The application of the BES is not limited to the traditional service format which only stores energy and delivers energy to users, but also provides a bulk energy service and ancillary services in the transmission and distribution systems, such as black start, voltage and frequency control, and demand-side management (IRENA, 2015; Hill et al., 2012). For example, the BES provides a frequency response in Doha, delivering smooth energy from the PV to the electricity system in New Mexico (EPRI, 2012).



(a) Conventional charging strategy (b) Optimized charging strategy

Figure 3.4 Solar PV and Energy Storage (IRENA, 2015)

In Germany, the distributed BES system is emerging in the commercial market. Recently, Sonnen Company, the BES manufacturer and provider, offered energy services to compensate for the power fluctuation in the electricity grid network. The individual residential BES behaves as the distributed virtual power plant to provide the primary operating reserve (Sonnen, 2018).

3.5.2.2 Thermal energy storage (TES) applications

Cooling energy is the main energy consumption in residential buildings in tropical countries. The BES application for providing cooling energy requires a large capacity to provide the energy demand for the entire building. The ice thermal energy storage (ITES) application is widely utilized in commercial buildings where the chiller operates at a low energy price period to store thermal energy, then provides chilled water when there are high energy prices. The ITES can be implemented with a renewable energy resource such as the PV system, storing excess energy generation during the day in the thermal energy storage tank and delivering cooling energy at night (Figure 3.5).

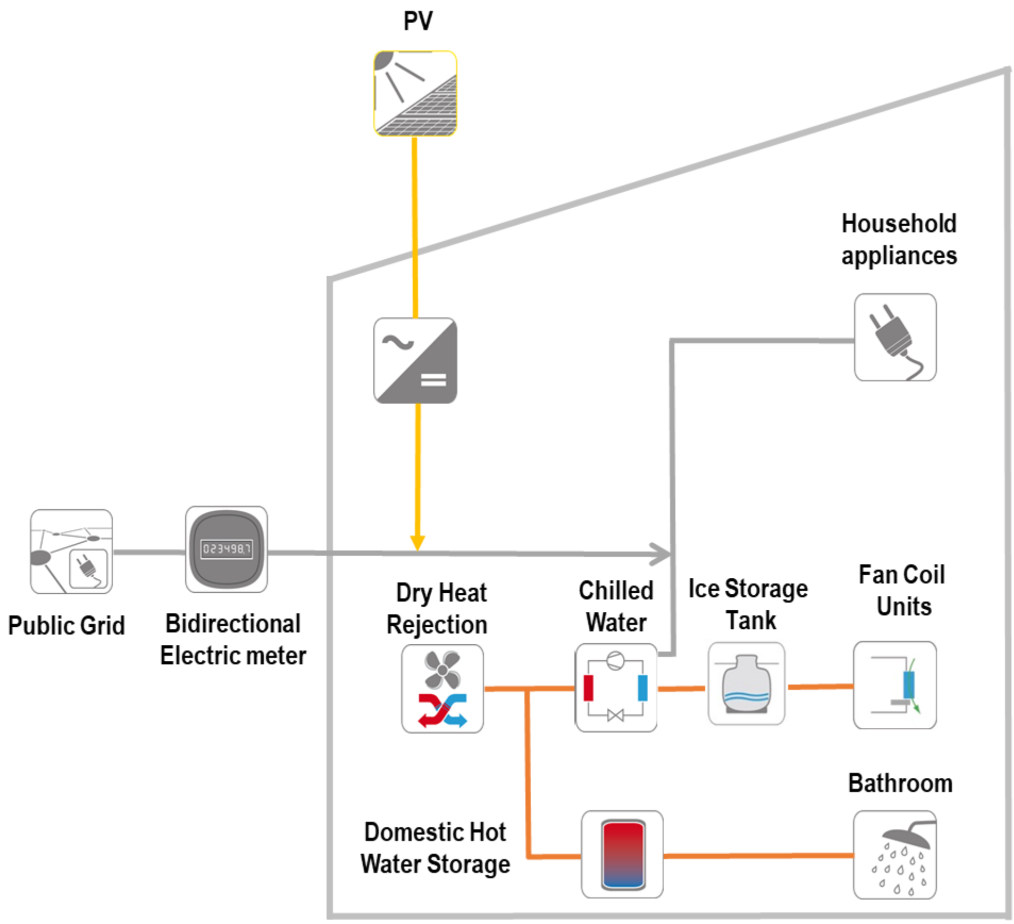


Figure 3.5 Ice thermal energy storage concept in a building (EGS, 2016)

The ITES application has many advantages for the end-user, such as increasing self-consumption from renewable energy resources, reducing peak load, shifting load from on-peak to off-peak, and flattening the load profile (Arteconi et al., 2013; Sehar et al., 2016). Experience in Japan shows that the peak shifting from the ITES in the commercial building is approximately 1.96 GW (JASE-W, 2015). The control strategy with electricity prices can save energy expenditures for the end-user. The utilization of ITES with full storage control strategy in office buildings in Thailand can save energy costs up to 55% per month under the time of use (TOU) scheme (Chaichana et al., 2001). Several studies have indicated that greater energy saving can be achieved by using storage control principles rather than the chiller priority method. This is because the chiller can run to meet the cooling demand under the storage control method (Ihm, 2014; Krarti, 2010; Levine S., 1999). The ITES application can also be deployed in residential buildings but requires a systematic design and a proven cost-benefit analysis.

3.5.3 Electric vehicle (EV)

The electric vehicle (EV) is becoming popular because it is environmentally friendly and has a more affordable cost (Tan et al., 2016). The EV is considered as the energy load and energy storage in the power system. The EV applications can be seen as the vehicle to grid (V2G) and vice versa, the vehicle to building (V2B), or vehicle to vehicle (V2V) (Figure 3.6).

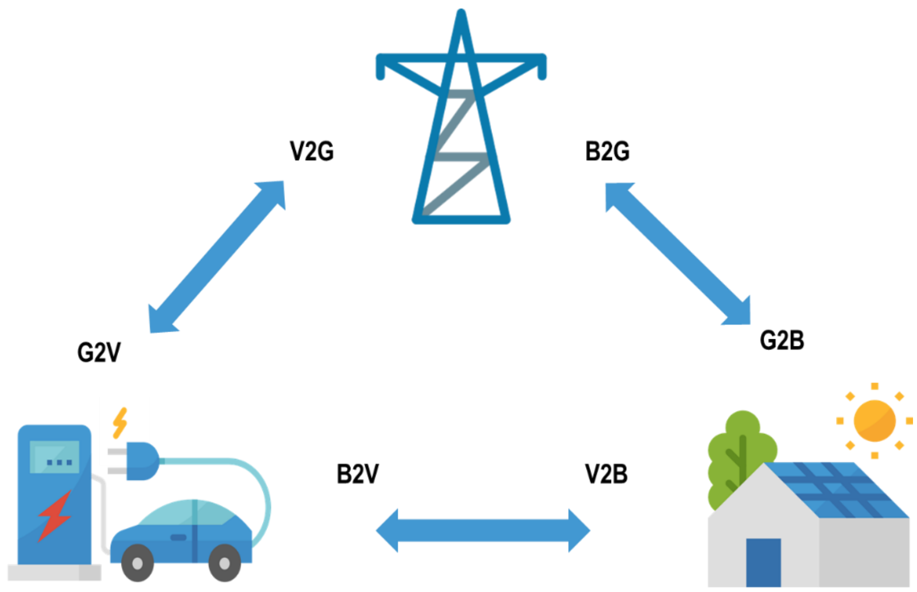


Figure 3.6 Electric vehicle applications in the smart grid (Kempton et al., 2005)

The V2G performs as an energy source by discharging energy from the battery to the grid and vice versa (G2V) (Zhang et al., 2012; Lamedica et al., 2015; Bishop et al., 2013). The V2G application can provide load shifting and flatten the load demand (Fattori et al., 2014; López et al., 2015). The V2B exchanges the electric power between the EV and the building or home (V2H), while the V2V trades electricity among them (Kempton et al., 2005).

Considering the EV in the smart grid, whether in unidirectional or bidirectional approaches, requires an energy management system and optimization control strategy for the mutual benefit of the EV owner and the electric utility.

3.6 Consumer behavior in the smart grid

3.6.1 Consumer perception toward smart grid

The smart grid empowers a traditional consumer to become a proactive consumer who responds to price signals and manages energy consumption lifestyles. Even more so, the smart grid allows a traditional consumer to become a prosumer who consumes and generates energy (Verbong et al., 2013; Potter et al., 2009; Mah et al., 2012). However, the smart grid knowledge of the consumer is diverse depending on several factors: education, perception, and daily lifestyle.

The smart meter is a smart grid technology that is implemented at the end user for real-time monitoring and management. The consumer desires the smart meter if it is not costly, but they lack understanding of why they are being installed and there is a misperception of what “smart” means. There are several studies that have indicated the non-technical issues, such as misperception, overexpectation, consumer privacy, and data protection, may prevent the smart meter rollout deployment (Naus et al., 2014; Krishnamurti et al., 2012; Crispim et al., 2014). The Netherlands is one of the EU member states who took this obligation very seriously by setting up the privacy and personal data protection legislation on the smart meter (Kloza et al., 2015). The advanced technology has a great advantage to the end user if it is deployed systematically by taking consumer behavior and economic feasibility into consideration.

3.6.2 Information flow invention for behavior change

Information and feedback can induce consumer behavior change. General information and historic feedback through email portals and reports without particular data are not effective for consumer behavior change (Faruqui et al., 2010; Naus et al., 2014; Ofgem, 2011; Schultz et al., 2015). Instead, accessible useful data channels through the in-home display (IHD) or web-portal are considered the most useful feature for consumer behavior change (Ofgem, 2011; Faraqui et al., 2010; JRC, 2017) (Figure 3.7).

Figure 3.7 Smart meter and in-home display (CSE, 2018)

However, it depends on the consumer choice if they require the additional real-time display with the extra cost (Kaufmann et al., 2013). The effectiveness of the information and feedback depends on several factors such as its frequency, duration, content, breakdown, the medium of presentation, and social comparison (Carroll et al., 2014; Hargreaves et al.; 2013; Ofgem, 2011). The norm feedback on in-home display, which shows both energy consumption in kWh and the expense cost in monetary terms, can reduce energy consumption compared to those households without feedback (Bariss et al., 2014; Schultz et al., 2015; Ofgem 2011). The information flow (between the household member, neighbor, and energy providers) would establish a new type of energy practice for consumer behavior change in the future (Naus et al., 2014).

The technology can enhance the consumer behavior change by considering the social norm, such as mental activity, daily lifestyle, background knowledge, motivation, level of emotion, perception, and know-how (Rechkwitz, 2002).

3.7 Pricing mechanism inventions

3.7.1 Demand response (DR)

A demand response program encourages the consumer to shift the energy demand during the on-peak to off-peak period by offering an incentive (Goulden et al., 2014; Torriti et al., 2010). The DR cannot be implemented without the smart meter and dynamic electricity pricing schemes. It should be noted that every country that has installed a smart meter does not yet have dynamic pricing designs in place (Faruqui et al., 2010). The value of the DR can be evaluated by the amount of peak demand reduction, which is associated with the investment of new power plants, transmission line systems, and distribution systems (Alexander, 2010; Bariss et al., 2014). The DR provides the peak shaving and load shifting while the energy efficiency measure reduces the overall energy demand.

The energy reduction under the DR program is varied by a context that consists of the price signal, consumer behavior, and policy measures. The DR pilot project in Germany indicated a load shifting potential of around 6-8% while the study in Italy has a peak reduction of 1.6-4.2% (Torriti et al., 2010; PPC, 2016). The commercial and industrial sectors have high potential for peak reduction because of the higher energy consumption (Crispim et al., 2014). Direct load control through smart thermostats provides a response and guarantees peak load reduction, but it could result in a big brother concern or nag behavior to the consumer. Adopting the pricing signal scheme and the smart device control with user interface display can enhance the DR implementation and behavior change in the residential sector (JRC, 2011; Ofgem 2011).

3.7.2 Dynamic pricing

Several dynamic pricing mechanisms are offered to the end user under the DR program for load shifting. For example, time of use (TOU), real-time pricing (RTP), critical peak pricing (CPP), and peak time rebate (PTR) (Bariss et al., 2014; Alexander, 2010) (Figure 3.8).

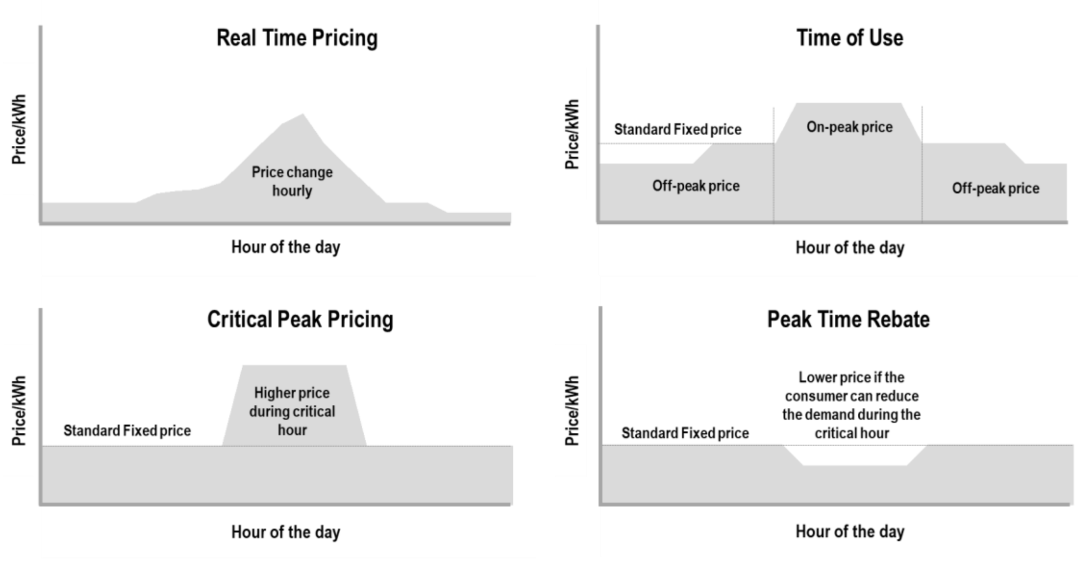


Figure 3.8 Flexible electricity price schemes (Faruqui et al., 2010)

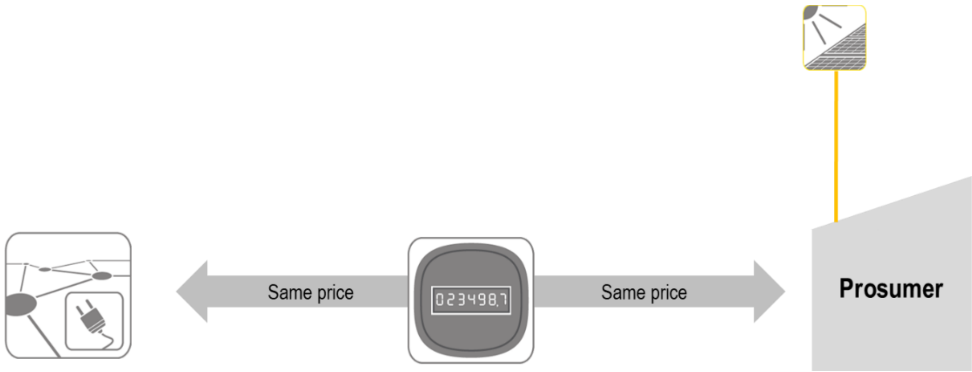
It should be noted that TOU is not dynamic pricing, as it is not dispatched based on the changes in actual wholesale market prices (Faruqui et al., 2010). The PTR provides cash rebates for each kWh of load reduction, while CPP charges a higher price during peak hours. Several studies have indicated that the PTR mechanism is a more favorable option to the consumer than the CPP program (Bariss et al., 2014; Alexander, 2010; Faruqui et al., 2010).

The CPP and TOU cannot guarantee peak load reduction if the participants can afford a high electricity price for their comfort. The PTR has a greater impact rather than the CPP scheme due to the consumers not being forced (Alexander, 2010; Bariss et al., 2014). Although the dynamic pricing is more complicated than the fixed tariff and the TOU scheme, the great advantage is it can encourage consumer behavior regarding the real electricity price signal.

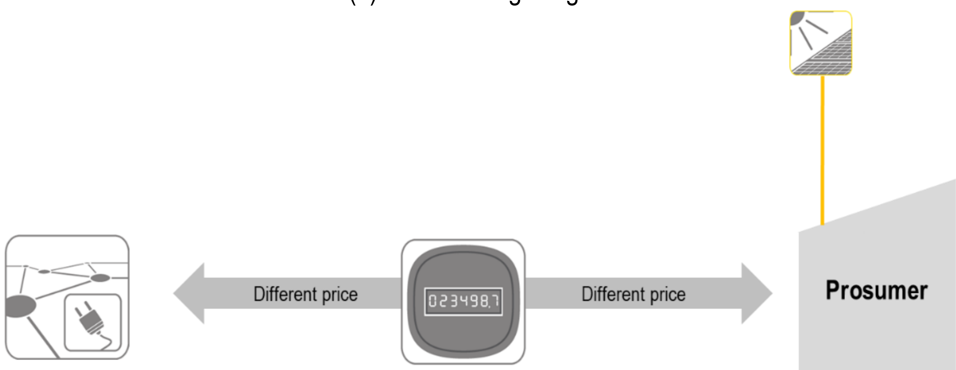
3.7.3 Net metering and net billing program

The feed-in tariff is the classical incentive scheme for buying electricity from renewable energy under a specific time period. The net metering measure promotes the self-consumption of renewable energy by purchasing excess electricity at a higher price than conventional fossil fuel. The bi-directional electricity meter will run backward if there is excess electricity fed back to the grid with the same electricity price.

Recently, there is another mechanism that is similar to the net metering called “net billing”. The net billing program has two electricity meters with one direction, or one electricity meter with two data records for the consumption from the grid, and the excess electricity fed into the grid (Dufo-López & Bernal-Agustín, 2015; Watt et al., 2015) (Figure 3.9). The reason behind the net billing scheme is to value the excess electricity and consumption from the grid separately.



(a) Net Metering Program



(b) Net Billing Program

Figure 3.9 The difference between the net metering and net billing program (Dufo-López & Bernal-Agustín, 2015; Watt et al., 2015)

The advance pricing design scheme of buying electricity from the renewable energy project is a wheeling charge that represents the electrical infrastructure cost (NREL, 2015). The wheeling charge represents the fairness mechanism in the energy market between prosumer and consumer. While the consumer pays the service fee to the utility in the retail electricity price, the prosumer pays the wheeling charge for using the electricity infrastructure for selling electricity. The wheeling charge rate is dependent on capacity, location and time period, which require intensive data and research for calculation.

3.8 Overview of smart grid policy

3.8.1 Smart grid policy in European Union (EU)

The smart grid is implemented in a different context on a country smart grid roadmap. The smart grid task force (SGTF) was established as the umbrella for smart grid deployment in the EU. A budget of EUR 5.5 million was invested for 950 smart grid projects to all EU member states. The investment is to demonstrate smart grid pilot projects in the member states and address the key smart grid technology, standards, regulations, and requirements toward a low carbon economy in 2050 (EC, 2011; JRC 2017; EC, 2012). A critical requirement of the early smart grid deployment is the harmonized standard and interoperability of the smart meter for electricity and gas. Consequently, smart network management is the focus in several countries in the EU (Figure 3.10).

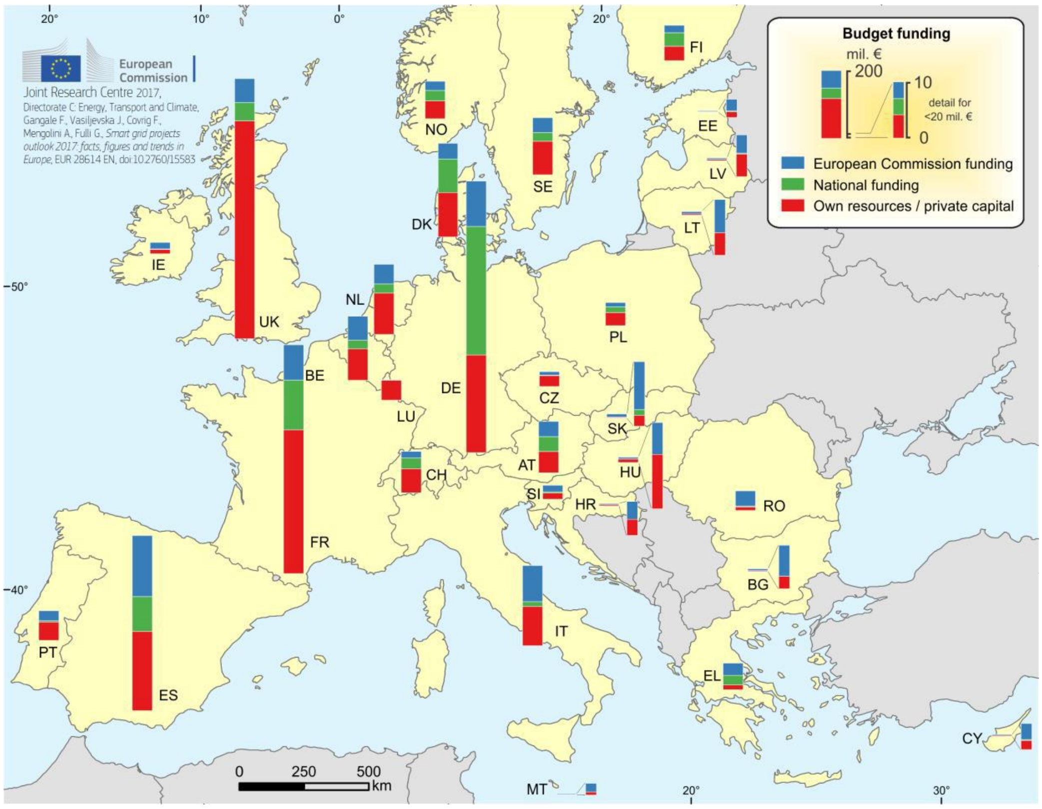


Figure 3.10 Percentage distribution of total investment by smart grid projects and country (JRC, 2017)

The EU aims to roll out the smart meter at a minimum of 80% of the electric meter by 2020 wherever it is cost-effective. Each member conducts the cost-benefit analysis based on EU guidelines. The energy saving from the smart meter is uncertain, as it depends on the country context and technology features (EC, 2015b). The interoperability of the smart meter is essential to providing universal and secure communication between the utility and the consumer, as well as between member states. Data privacy and security must be taken into consideration for smart meter deployment where the personal data should not be published without prior user consent.

The short-term smart grid policy in the EU at the end user mainly focuses on energy efficiency measures and demand-side management (DSM), rather than the demand response program, because the smart meter and market potential is not in place yet (Torriti et al., 2010). The regulatory incentive framework for the smart grid is based on improving energy efficiency and avoiding peak demand investment, rather than providing additional sales to the distribution system operator. The learning process “along the way” approach allows the member states to learn the best practice and technology specification requirement for a full smart grid implementation in the future (EC, 2012).

The list of lesson learned for the smart grid project at the end user is shown in Appendix 1.

3.8.2 Smart grid policy in the USA

The national smart grid policy was developed in 2011 to frame the future energy system of the USA. Similarly, each state in the USA has its own implementation plan and regulation as in the EU. There are four pillars for the smarter grid transformation: 1) Enable cost-effective smart grid investment, 2) unlock the potential of innovation in the electricity sector, 3) empower the consumer and enable informed decision making, and 4) secure the grid. The standard is the key factor implementation for the smart grid development in the USA, and therefore the National Institute of Standards and Technology (NIST) was assigned to be responsible for smart grid deployment in the US. The area of smart grid technology includes the customer system, smart meter, electric distribution system, electric transmission system, and equipment manufacturing (NIST, 2012; EIA, 2011).

The smart meter is being deployed extensively in the USA. As of 2016, 88% of the smart meter installation is deployed in the residential consumer (IEI, 2017) (Figure 3.11). The benefit from the smart meter in the USA is it can induce the net metering and demand response program in over 40 states. The smart grid budget is approximately EUR 8 billion through demonstration projects, workforce training, resource assessment, transmission planning, and smart grid projects (SGIG, 2007).

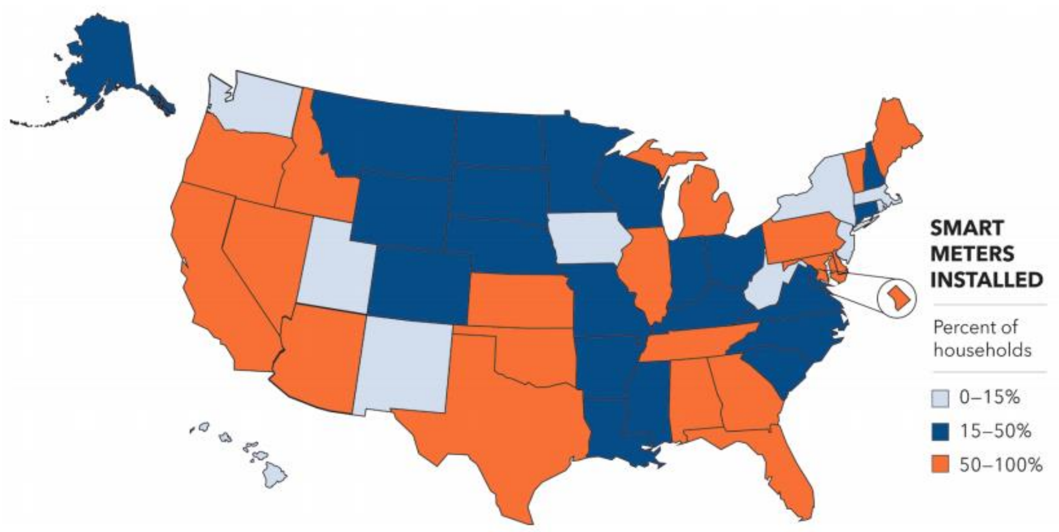


Figure 3.11 Smart meter deployment in USA (IEI, 2016)

The successful smart grid deployment at the end user is mainly from the smart meter, smart appliances, and dynamic pricing. Financial support is considered as the key barrier for smart grid deployment in the USA where the budget shall be allocated appropriately for smart grid projects adoption (CRS, 2018). Cybersecurity and privacy concerns are considered as crucial factors for smart grid deployment in the USA.

3.8.3 Smart grid policy in Thailand

The smart grid roadmap in Thailand was initiated by the electricity utilities. In 2015, the Energy Policy and Planning Office (EPPO) under the Ministry of Energy developed a national smart grid master plan by integrating the smart grid roadmap made by the utility industry. It is quite uncommon for a national energy policy to be developed after the utility industry, but this was because Thai utilities are active in improving their electrical system.

The national smart grid roadmap aims to improve the electricity system by focusing on five aspects, which are 1) power reliability and quality, 2) energy sustainability and efficiency, 3) utility operation and service, 4) integration and interoperability, and 5) economic and industrial competitiveness (MOE, 2013). There are five main areas for smart grid implementation: demand response, energy management, renewable energy forecast system, microgrid, and energy storage system (ESS) (Figure 3.12).

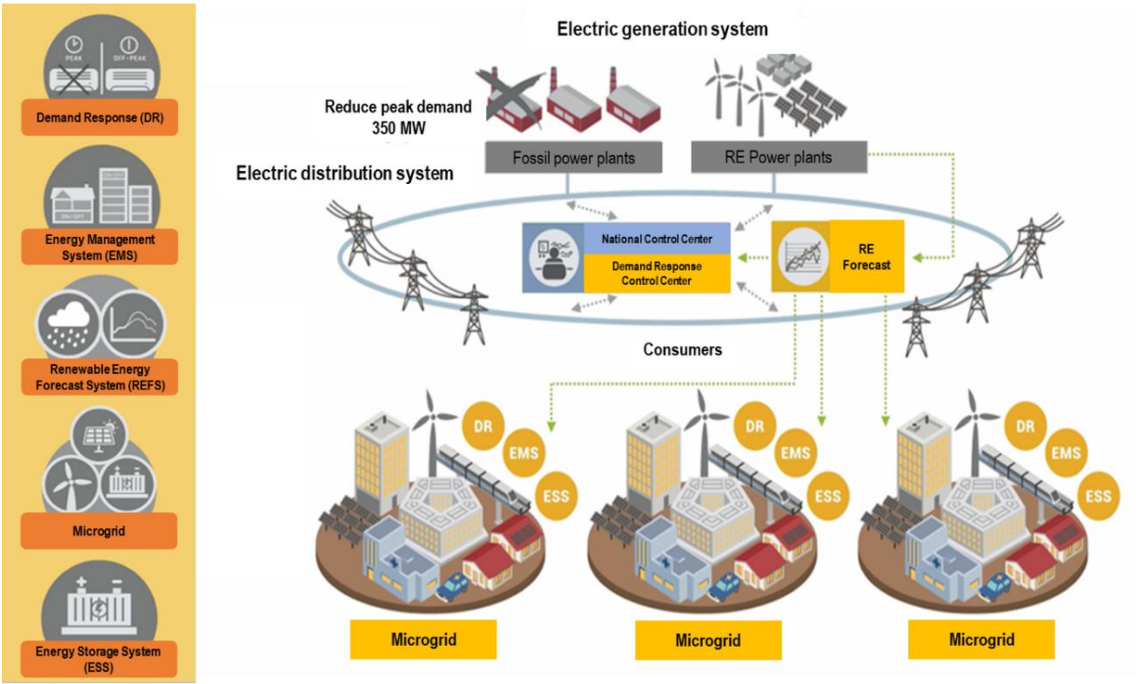


Figure 3.12 Smart grid roadmap in Thailand (MOE, 2013)

It can be foreseen that the national smart grid roadmap will tend to encourage clean energy into the system and empower consumer integration through the DR program. The DR program was first introduced as a voluntary program for the industrial and commercial sectors. The real DR deployment requires concrete regulation and attractive incentive design to empower end-user participation.

The status of smart grid development in Thailand is under the pilot stage, where the government focuses on technology potential and interoperability in action (EGAT, 2013; MEA, 2012; PEA, 2015). The key smart grid deployment of Thailand and electricity utilities is shown in Appendix 2.

1) Smart grid roadmap overview of Electricity Generating Authority of Thailand (EGAT)

The vision of the EGAT smart grid roadmap aims to be "the leader of green energy with a reliable electricity network in ASEAN" (EGAT, 2013). As EGAT's roles are in generating and transmission systems, smart grid technologies mainly improve the electricity network performance through information and communication technology (ICT), smart operation, enabling demand response between utilities, substation automation, SCADA for decentralized control, and online monitoring. Moreover, EGAT also focuses on green grid development by increasing the small scale of renewable energy with grid code harmonization and renewable energy forecast systems. The battery energy storage system will be deployed as the pilot project, with a large-scale renewable energy project to foresee the technical potential and cost-benefits for real deployment in the future. However, the EGAT smart grid roadmap is only responsible for electricity generation and transmission systems due to its authority's possibility to be implemented in medium and high voltage systems.

2) Smart grid roadmap overview of Provincial Electricity Authority (PEA)

The PEA smart grid roadmap consists of three main areas: smart energy, smart life, and smart community (PEA, 2015). As PEA is an electricity distribution utility, its smart grid roadmap will focus more on the distribution system, relating directly to the end-user in the residential sector. The smart meter pilot project will be deployed in 2019 in Pattaya city, in the Chonburi province in the east of Thailand at approximately 116,000 units (PEA, 2015). The purpose of the smart meter pilot project is to examine the interoperability of the technology for future smart meter rollout. The smart meter rollout plan is divided into three phases from 2022 to 2041, where 18 million smart meters will be installed in households throughout the country by 2036. Additionally, the old electricity meter, with its lifetime of over 10 years, will be replaced after the year 2036. However, the intensive cost-benefit analysis and provision of information of the smart meter are essential prior to future rollout deployment.

3) Smart grid roadmap overview of Metropolitan Electricity Authority (MEA)

The MEA smart grid roadmap focuses on sustainable system automation by deploying the smart meter and distribution management system. The roadmap will also implement the electric vehicle (EV) charging system for the end user, as the authority of the MEA covers Bangkok where the EV growth is expected to increase. However, the MEA roadmap does not have a specific smart meter rollout target compared to the PEA roadmap. At the end of the roadmap, the distribution system of the MEA will be able to perform a self-healing grid, full automation, and have electric vehicles as the distributed resource (V2G) (MEA, 2012). The MEA smart grid roadmap is very broad with general electricity system improvement.

3.8.4 Smart grid in Association of Southeast Asian Nations (ASEAN)

The smart grid is being deployed in several countries in the Southeast Asia region. Singapore is the only country in SEA that has deployed the smart grid pilot project since 2010, focusing on enabling infrastructure and rolling out smart meter development. Other countries except Singapore are testing the technology interoperability through pilot projects. The countries in Southeast Asia highly require guidelines and lessons learned from experts, especially in technical requirements and standard harmonization. Currently, there is no ASEAN smart grid roadmap at the regional level as in the European Union. Each country in the Southeast Asia has developed its own roadmap depending on the country and the electricity market context. The regional smart grid roadmap would frame the development in the same direction. The current smart grid development in each country in SEA is shown in Appendix 3.

3.9 Conclusion

Smart grid policy varies by the country's context. Smart grid deployment can be seen both at the electrical supply system and at the end user. The key smart grid technology for electricity utility is integrating the information and communication technology features into the existing system for real-time monitoring, advanced optimizing, and self-healing systems. The smart grid also enables the traditional consumer to become the proactive consumer and prosumer. The lesson learned from the European Union (EU) has shown that a building with integrated technologies can contribute new energy services to the electricity network.

The building can perform as the power plant by integrating renewable energy resources and an energy storage system. The battery energy storage (BES) system can provide ancillary services to the electricity grid network, such as smoothing the power fluctuation, frequency response, and voltage control. Thermal energy storage (TES) offers useful energy such as cooling and heating energy to the end-user that can reduce the reversed power flow from the variable renewable energy in the electricity grid network.

The demand response program encourages the proactive consumer to shift the load during the on-peak period by offering dynamic pricing schemes. However, the demand response and net metering programs can only be implemented if the smart meter is in place. Smart meter deployment has also raised privacy and cybersecurity concerns to the consumer, requiring data protection legislation. The information flow invention can enable consumer behavior change and a proactive consumer role in the smart energy system.

In Thailand, the electricity utilities and not the government first initiated a smart grid roadmap. While Thai electricity utilities aim to install the smart meter at the end user to enable the real-time energy service, the knowledge of its benefit and effects should be provided prior to the deployment. A national smart grid roadmap of Thailand aims to enhance the proactive consumer and prosumer, and the residential sector can play an important role with the appropriate integrated technologies. The potential technologies are available in the market, but it is very challenging for Thailand because of lacking the appropriate smart grid policy and an incentive for the residential sector. A technical assessment with the economic, social and regulatory circumstances can address the potential energy practice approaches for the residential sector in smart grid development.

- empty page -

Chapter 4

Assessment of Integrated Technology Applications in the Residential Building in Thailand

4.1 Introduction

The residential building can behave as the power plant in the smart grid context by integrating technology applications to provide energy services to the electrical network. The electricity demand average growth rate in the residential sector of Thailand is approximately 5% per year (EPPO, 2017a). It is expected that the electricity demand in the building sector for ASEAN countries will more than double by 2040, mainly driven by cooling demand (IEA, 2017a). The energy design concept in a residential building is highly essential to integrate it into the smart grid context.

This chapter presents the evaluation of technology applications' potential for residential buildings in Thailand, compared with the reference building. The environmental impact will be also assessed and presented at the end of the chapter.

4.2 Residential building in Thailand

Thailand has different types of residential buildings, which are a detached family house or a single-family house, townhouse, condominium, and apartment. The National Statistic Office (NSO) in Thailand has collected the number of households categorized by building type every ten years. The latest data has shown that the single-family house is the majority building type of Thailand by accounting for 72% of total households in Thailand (Figure 4.1) (NSO, 2010; REIC, 2018).

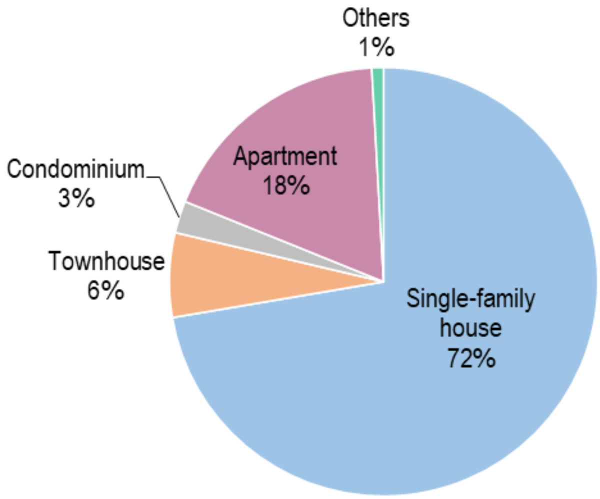


Figure 4.1 Share of residential building type in Thailand (NSO, 2010)

The number of new construction areas for single-family houses is higher than other types of residential buildings by taking 65% of total new construction area in 2018 (Figure 4.2).

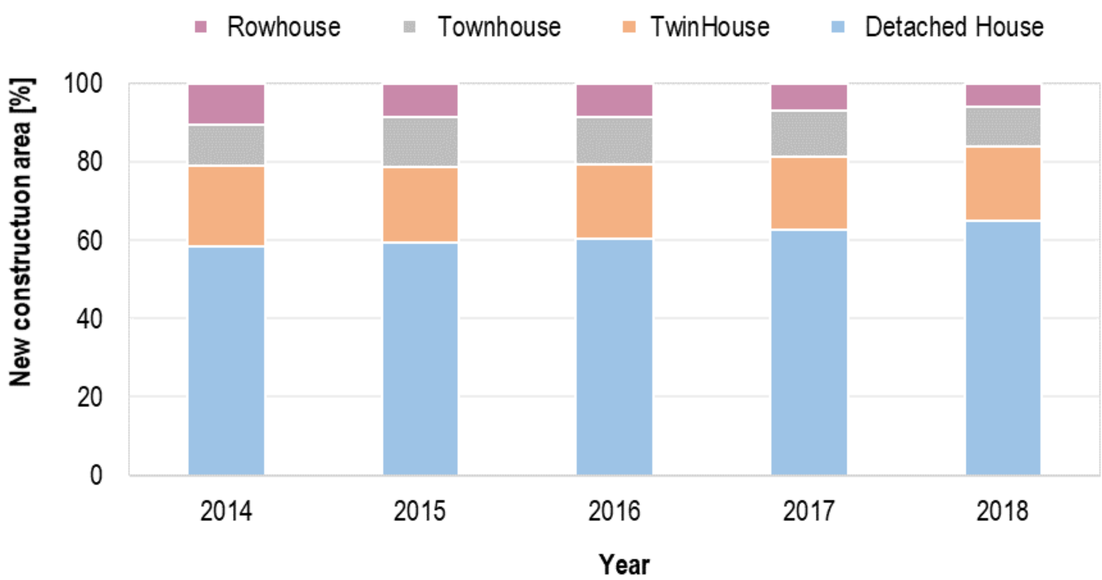


Figure 4.2 Share of new construction area of residential buildings in Thailand (NSO, 2018)

In 2018, Bangkok has 31% of total new construction of single-family houses in Thailand, followed by the northeast (Figure 4.3).

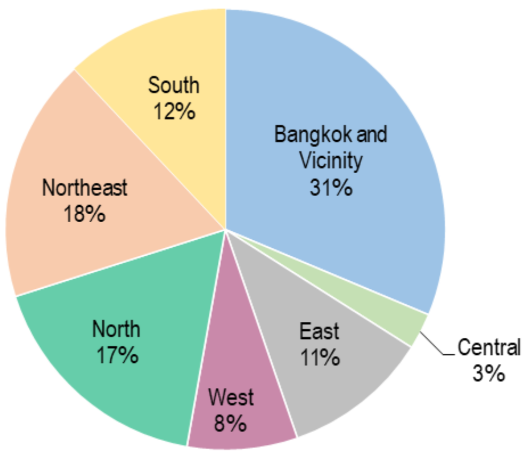


Figure 4.3 Share of new construction of single-family houses in Thailand by region in 2018 (NSO, 2018)

The increasing of new single-family houses in Thailand, especially in Bangkok, raises the concern of high energy consumption in the residential sector in Thailand in the future. Investigation on energy design options in single-family houses is essential to enhancing typical single-family houses to become energy efficient buildings in smart grid development.

4.3 Methodology framework

The scope of this research only focuses on the detached single-family house, which is the majority building in the residential sector, accounting for 78% of total residential building areas of Thailand (NSO, 2010). The integrated technology options in this research focus on reducing the energy consumption in the building and then meeting the remaining demand with renewable energy resources. The general load profile of the residential building rises in the morning and evening on weekdays, resulting in a mismatch between energy demand and energy supply from the PV system. The energy storage system is considered to increase the PV self-consumption (Figure 4.4).

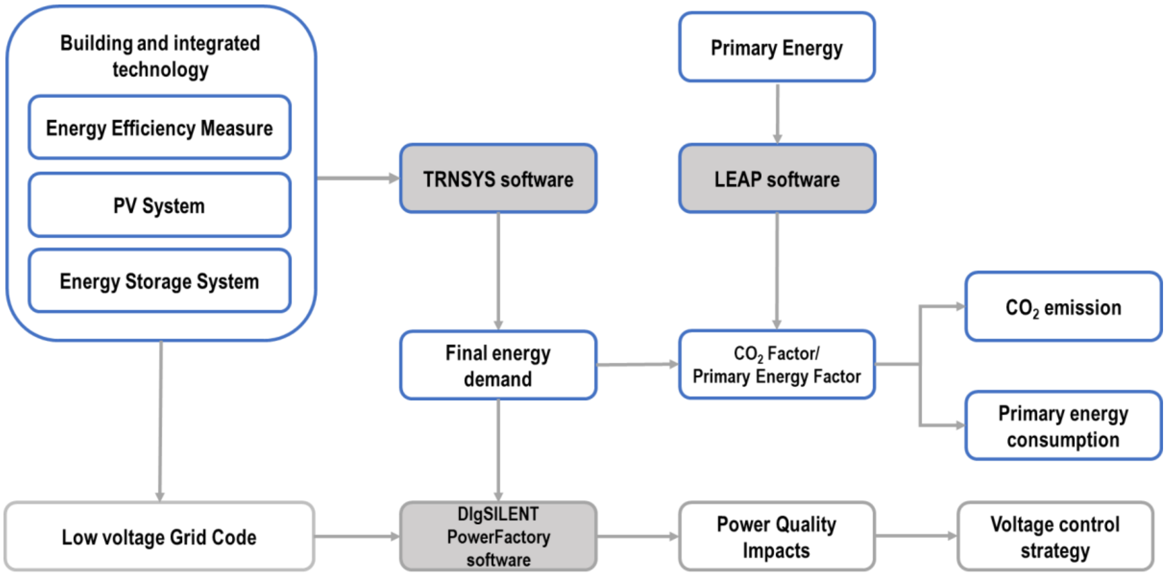


Figure 4.4 Technology assessment framework

The building with integrated technologies is simulated in the TRNSYS software (Figure 4.5). The electricity demand in the building is converted to primary energy demand per square meter by using the primary energy factor (PEF). The CO_2 emissions are compared between the reference and alternative scenarios by using the CO_2 factor, which is calculated in the LEAP software by taking the power development plan (PDP) into the analysis.

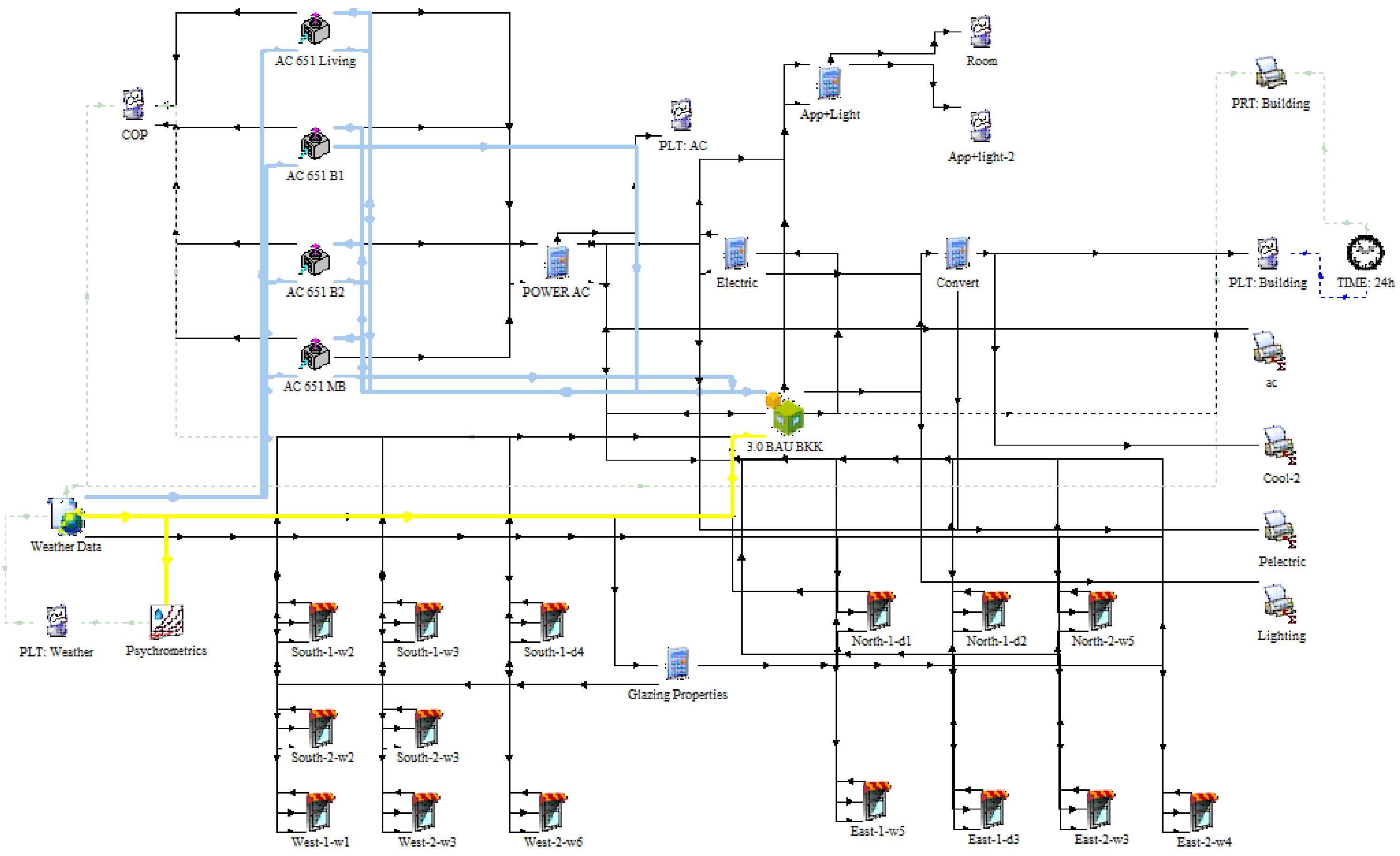


Figure 4.5 Simulation model in TRNSYS

4.4 Building type

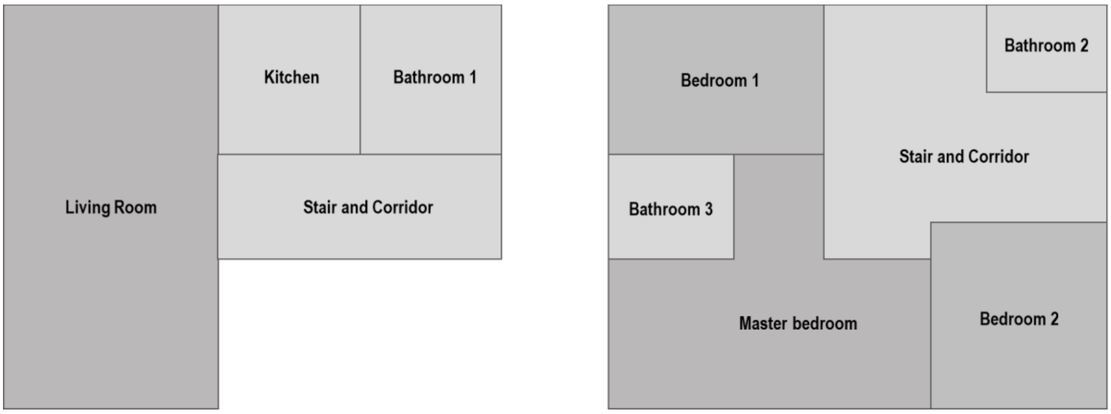
4.4.1 Reference building (REF)

The building energy code in Thailand is not mandated for a detached single-family house, and therefore it is built depending on the real estate developer to meet the users' satisfaction and also company profit. Most of the detached single-family houses have not integrated energy efficiency measures (EEM) (such as insulation, external shading, and double-glazing windows) to reduce energy consumption, but rather focus on the exterior and interior design with minimum investment costs.

The modern single-family house built by concrete, as shown in Figure 4.6 represents medium and high-income families in Thailand. This type of single-family building can be seen in the big cities such as Bangkok, Chiang Mai (the north), Nakhon Ratchasima and Khonkaen (the northeast) (NSO, 2010).

Figure 4.6 Reference single-family house perspective (REF) (Design: Preksa holding Co., Ltd)

The reference building (REF) represents a middle-class single-family house in Thailand for four occupants: two adults and two children. The reference building is a double-story detached house located with a gross floor area of 160.1 m^2, a net floor area of 141.4 m^2, and an air-conditioning area of 80.9 m^2. The building layout for the first and second floor is shown in Figure 4.7.



(a) First floor (b) Second floor

Figure 4.7 Layout of the reference building

4.4.2 Nearly zero energy building (nZEB)

The alternative building is called the nearly zero energy building (nZEB), retrieved from EGS Bangkok company (EGS, 2016) (Figure 4.8).

Figure 4.8 nZEB building perspective (Energy concept: EGS-Plan, Bangkok)

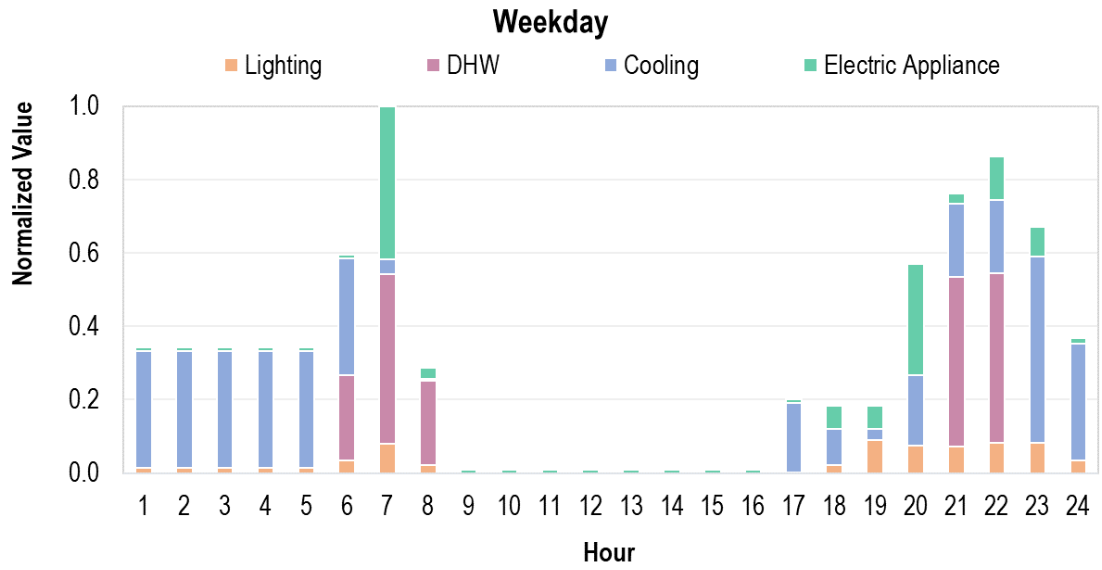
The nZEB building has the same floor plan as the REF building, but the thermal properties of the nZEB are better than the REF building, as shown in Table 4.1 . Generally, the REF building does not have airtightness technology which results in a gap between the walls and the roof, and between the wall and the window frame. The infiltration rate of the REF building and nZEB building is approximately 1.5 h^{-1} and 0.15 h^{-1}, respectively (Jareemit 2015; Iqbal et al., 2017).

Table 4.1 Building thermal properties

Element	**U Value (W/m^2K)**	
	REF building	**nZEB building**
Wall		
Internal Wall	3.30	0.59
Non-Insulated internal wall	4.59	4.59
External Wall	3.26	0.59
Non-Insulated External Wall	4.14	4.14
Roof	2.53	0.42
Window		
Glazing U_g value	5.68	1.76
Frame U_f value	5.80	1.76
Solar transmittance	0.86	0.60
Entrance Door	1.24	1.24
Ground		
Ground floor	3.31	3.31
Ground floor (Bathroom)	4.00	4.00
Internal floor	2.00	2.00
Internal floor (Bathroom)	2.18	2.18

4.5 Energy demand profile

The energy demand in the residential building consists of cooling, lighting, domestic hot water (DHW), and electric appliances. The energy load profile of the building is categorized into weekdays and a weekend basis (EPPO, 2009) (Figure 4.9). The national holiday load profile is assumed to have the same profile as the weekend.



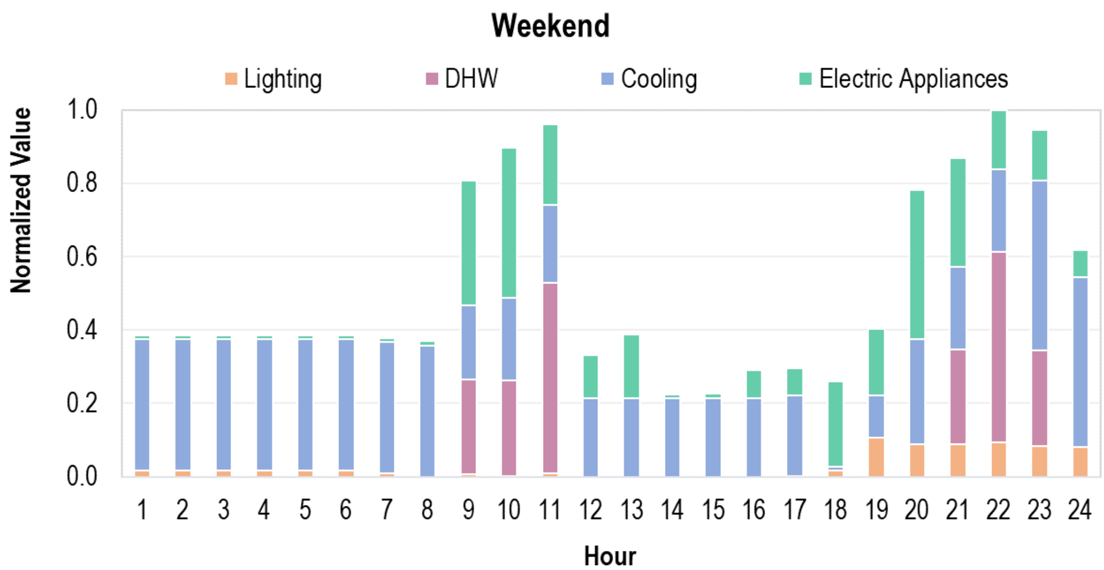


Figure 4.9 Electricity demand categorized by load on weekdays and weekends

The common load profile of the REF building is rising in the early morning when occupants prepare to go to work or school and again in the evening after they come back home. The main electricity consumption in the detached single-family is from cooling energy demand. Modern households in Bangkok do not cook very often during the weekdays, but prefer buying food from restaurants and warming it at home by using a microwave (MECON, 2014). Cooking activity is high at the weekend. However, this research assumes that the occupants use the cooking appliances on both weekdays and weekends.

4.5.1 Cooling demand profile

The split type air conditioning (AC) system is a common cooling technology in the typical detached single-family building of Thailand (Figure 4.10). It consists of the fan coil unit inside the building and the condensing unit outside of the building. The condensing units use the air as a coolant, which uses a fan to increase the cooling capacity.

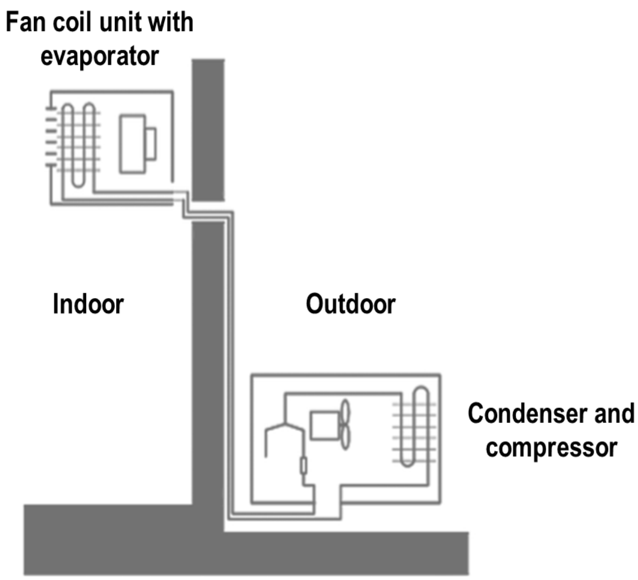


Figure 4.10 Split type air conditioning unit (DEDE, 2009)

However, the minimum standard coefficient of performance (COP) of the split type air conditioning system in Thailand is defined at 3.2. The practical COP value of the air conditioning under the real condition is a range between 2.0-2.2, depending on the lifetime, temperature and humidity control, maintenance, and cooling operation system (Phatidamrongkul & Varodompun, 2012). According to the energy standard in Thailand, the minimum COP value of fix speed split type air conditioning systems up to 27,896 Btu/hr is approximately 3.25 (EGAT, 2017a).

The occupants also contribute thermal energy which requires cooling energy demand in the building. This research assumes the sensible heat of 60W and latent heat of 40W for each occupant (TRNSYS, 2006). The appropriate thermal comfort for Thai occupants is set at 24 ^{o}C and relative humidity of 65% for the air-conditioned zones. In Thailand's context, the cooling device is activated whenever a person is in the respective room. In other words, the cooling devices are turned on and off by the occupants. Occupancy from 9:00 AM to 16:00 PM is almost zero during the weekday, meaning there are no occupants in the building (Figure 4.11).

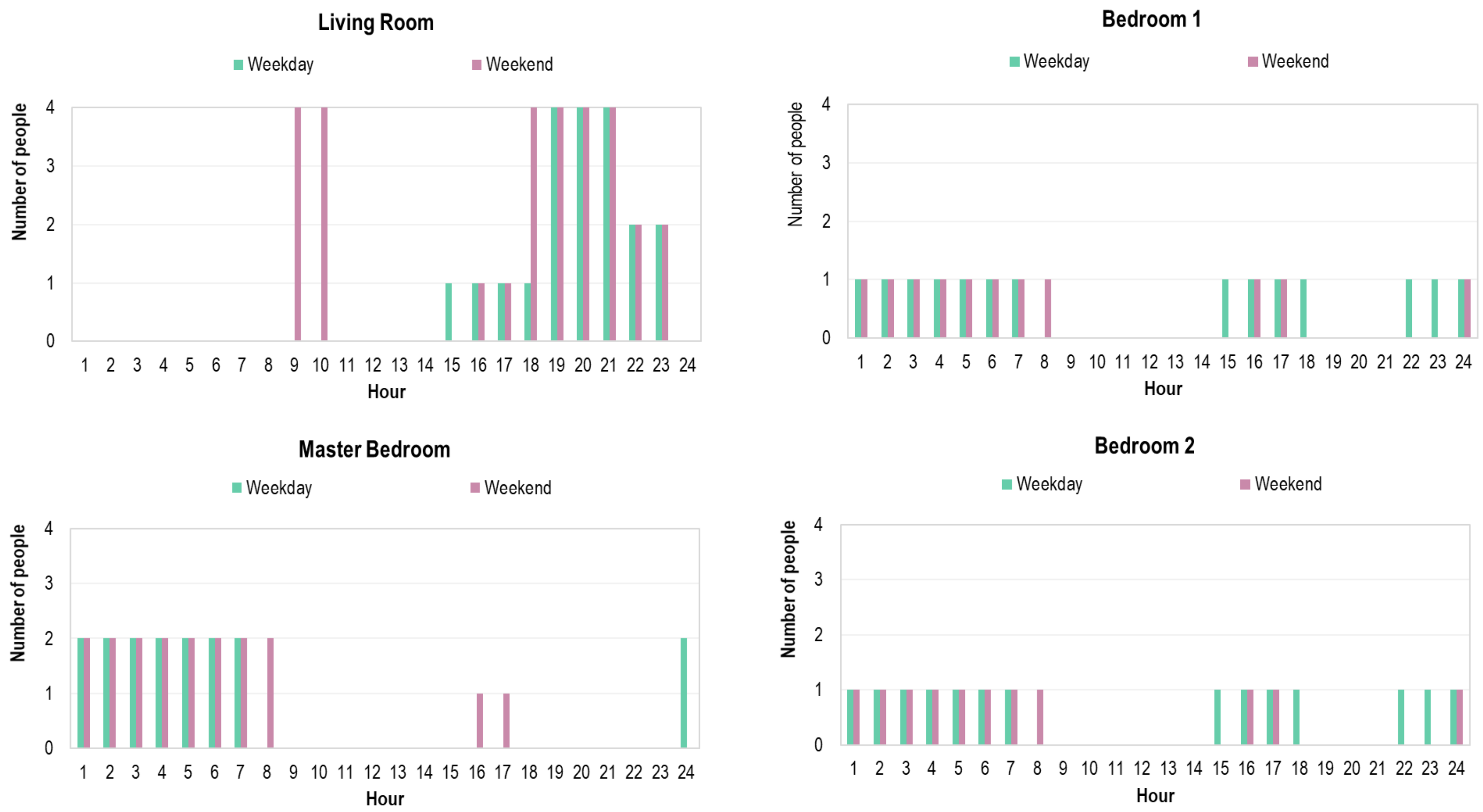


Figure 4.11 Occupant profile in each room

4.5.2 Electric household appliances

The average electricity demand for electrical household appliances in this research is assumed at 10 kWh/(m^2a) (EGS, 2016).

4.5.3 Lighting

The average electricity demand for the lighting system is assumed at 4.4 kWh/(m^2a) to provide appropriate illumination in the building (EGS, 2016).

4.5.4 Domestic Hot Water (DHW)

In Thailand, the typical water heater technology provides domestic hot water in the bathroom. In this study, the electricity demand of DHW is assumed at 12 kWh/(m^2a) (EGS, 2016).

4.6 Primary energy factor

The primary energy factor (PEF) is used to convert the primary energy (Q_p) to final energy (Q_E) (Figure 4.12) as shown in Eq. 4.1. In other words, the PEF refers to the efficiency of the system by indicating how much of the primary energy is needed to generate one unit of final energy. The calculation is based on the life cycle calculation (Wilby et al., 2014; ECOFY, 2011). The PEF value varies by country due to the different energy systems. The PEF for electricity in Thailand was 2.5 in 2017.

$$Q_P = PEF \times Q_E \qquad \text{Eq. 4.1}$$

Figure 4.12 Primary Energy Factor (PEF)

4.7 Energy concept scenarios

The REF and nZEB buildings are considered in each scenario to show the impact of energy efficiency measures. The technical concept of each scenario is shown in Figure 4.13. In this study, there are four scenarios for different energy concepts as follows:

1. Grid scenario: building without PV
2. GridPV scenario: building with PV system
3. GridPVITES scenario: building with PV system and ice thermal energy storage system
4. GridPVBES scenario: building with PV system and battery energy storage system

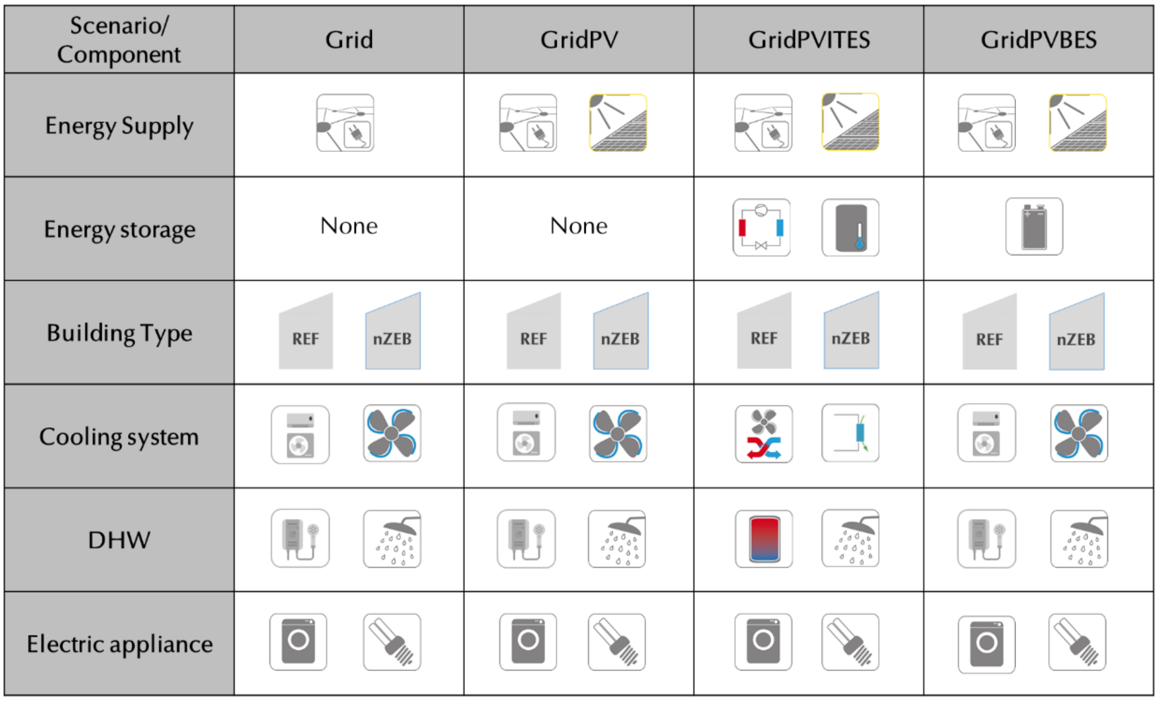
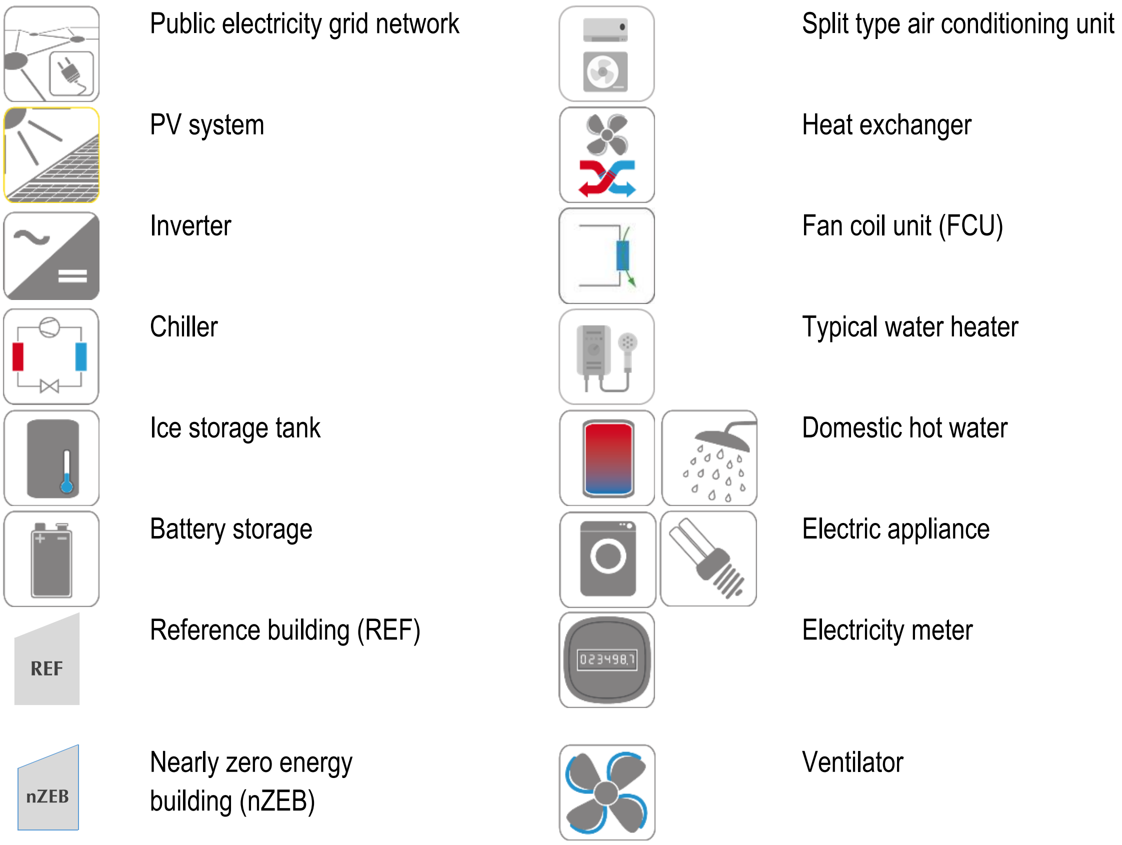


Figure 4.13 Simulation scenarios

Symbol and description



4.7.1 Grid scenario

The Grid scenario presents the current situation of the typical residential building in Thailand. The building is connected at the low voltage (LV) of a 220 Volt electrical grid network (Figure 4.14). The cooling demand is provided by the split type air conditioning unit and the domestic hot water is supplied by traditional electric water heater technology.

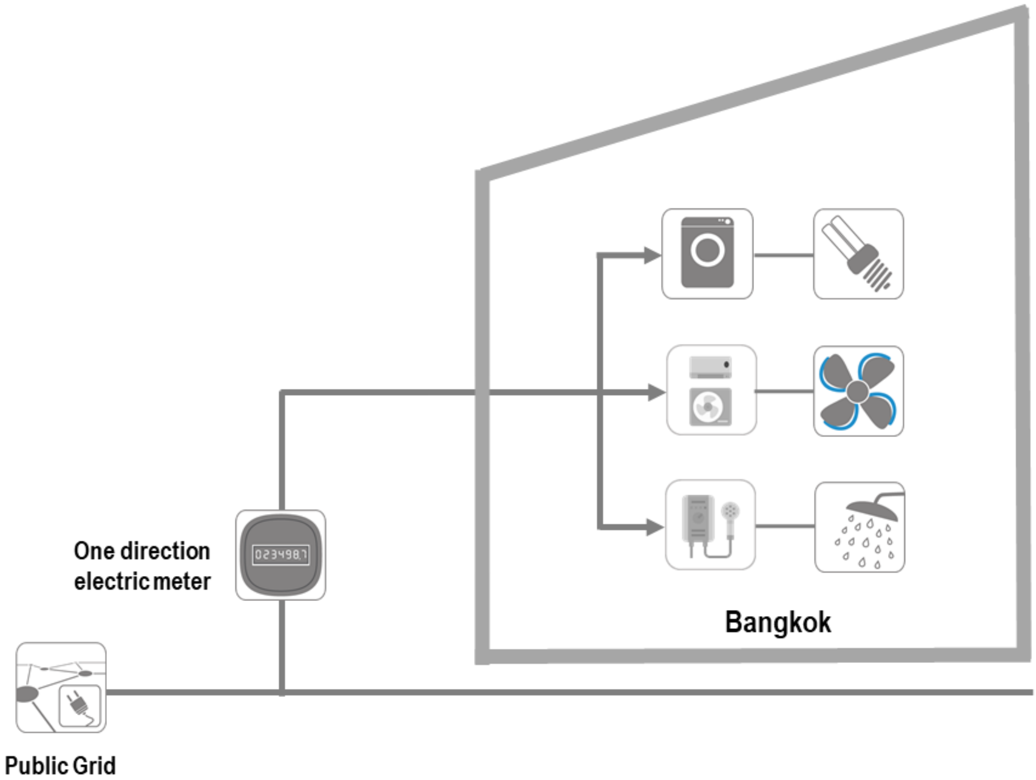


Figure 4.14 Energy concept of the Grid scenario

4.7.2 GridPV scenario

The emergence of distributed PV in the residential sector is taken into consideration in this scenario. The GridPV scenario presents the building, which is supplied by the national electricity grid network, and the PV system on the roof. The building is equipped with 5 kWp of PV. The excess energy from PV is fed into the national electric grid (Figure 4.15).

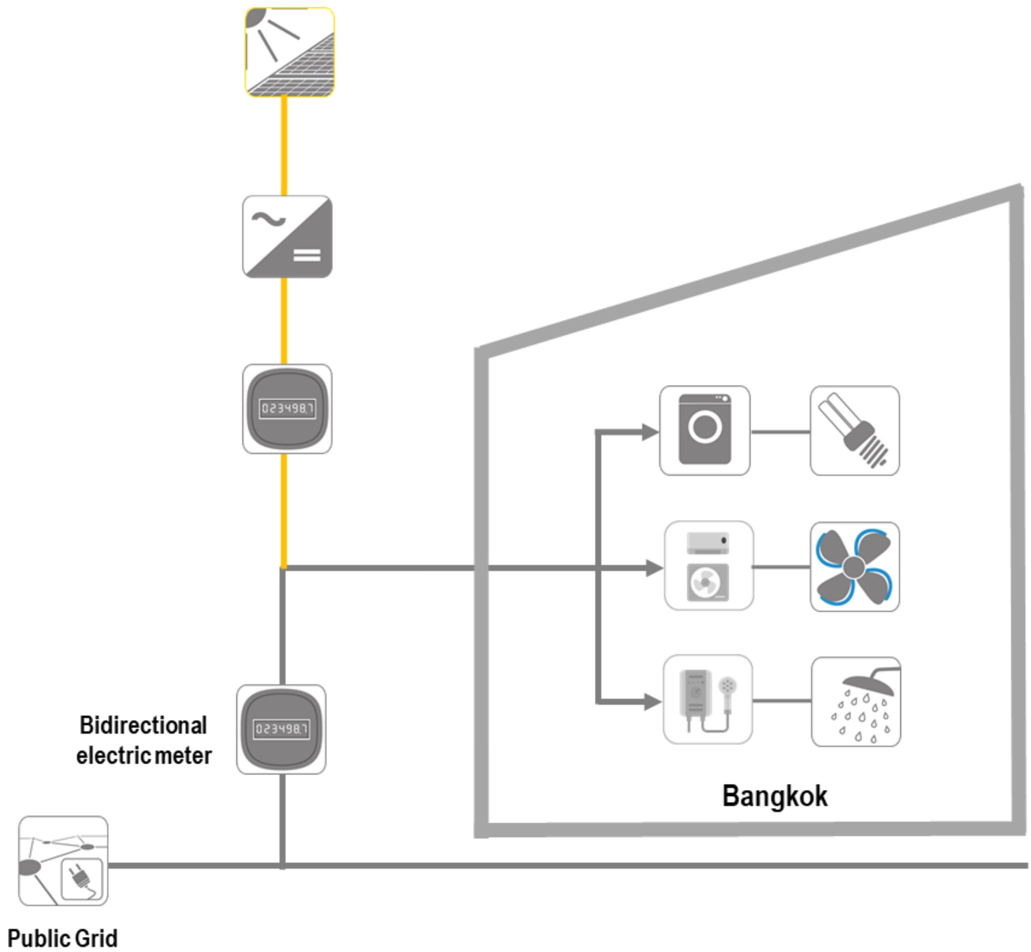


Figure 4.15 Energy concept of GridPV scenario

The absence of PV generation in the evening will be covered by the national electricity grid. The cooling demand is provided by the split type air conditioning unit and the domestic hot water is supplied by the traditional electric water heater technology as the Grid scenario. The energy storage system does not exist for this scenario.

4.7.3 GridPVITES scenario

The mismatch of energy demand and supply of the residential building has driven the importance of the energy storage system. The cooling energy demand is the main energy consumption in the residential buildings of Thailand. Therefore, it is reasonable to store energy from the PV system during the daytime and provide cooling energy to the building in the evening by ice thermal energy storage systems (ITES).

This scenario represents the building with 5 kWp of PV and the ITES. The building is also complemented by the national electricity grid when there is an absence of solar energy (Figure 4.16). The main outstanding feature of the GridPVITES scenario is the cooling energy system, which is supplied by the ITES system instead of using the typical split air conditioning unit.

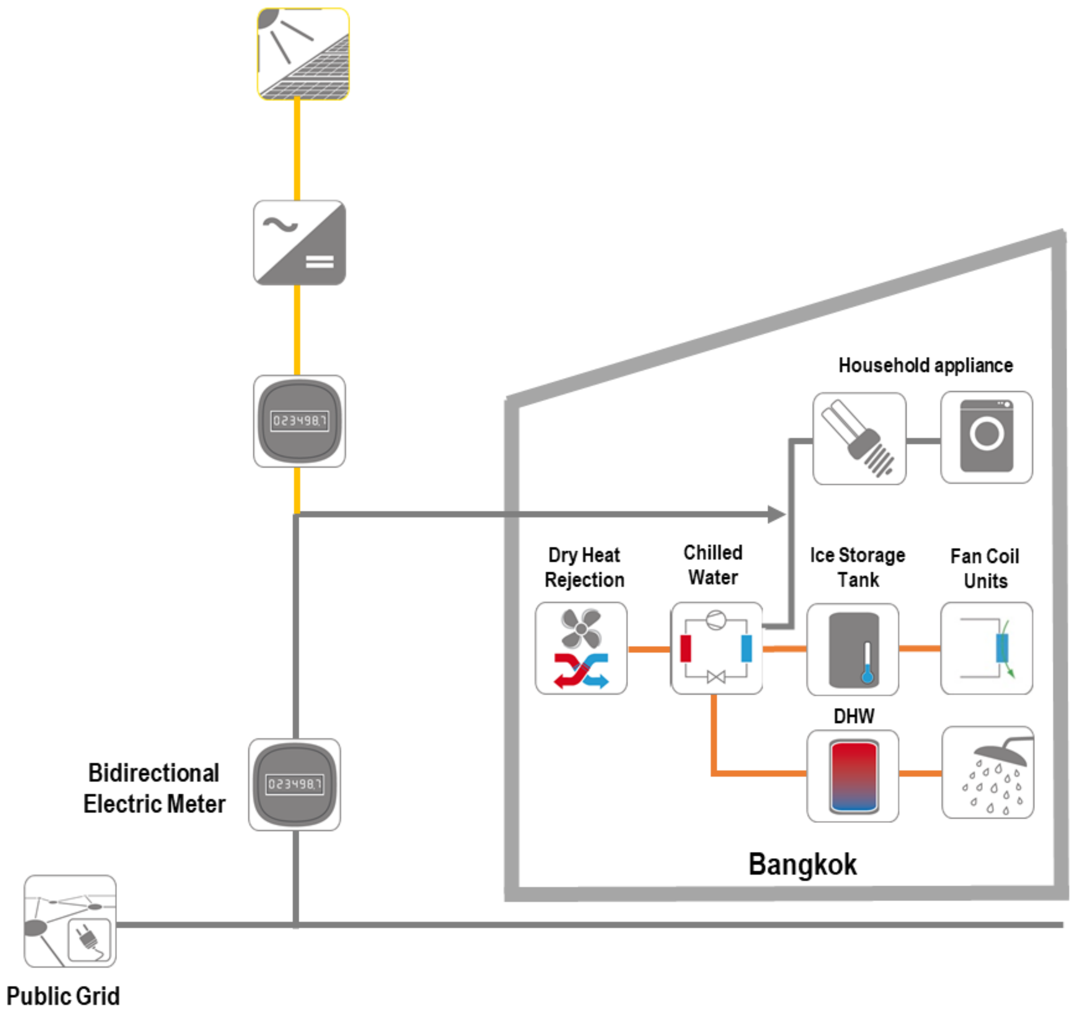


Figure 4.16 Energy concept of GridPVITES scenario

During the day, the energy from PV is utilized by the chiller (i.e. reversed heat pump) to generate low-temperature ethylene glycol, and is delivered through the pipes in the storage tank. The ice grows around of the pipes in the 1,000-liter cylinder storage tank (radius 0.4 m x height 2.4 m) to meet the cooling load of the building (EGS, 2016). In the evening, the warmer chilled water is circulated around the pipe in the storage tank to melt the ice and provide the chilled water of 7 °C to the fan coil units (FCU) in the building. If there is no sufficient ice in the storage tank, then the electricity from the national electricity grid is supplied to the chiller. The advantage of the waste heat is that it is used to generate domestic hot water (DHW) of approximately 42 °C for the bathroom in the master bedroom. This can reduce the energy demand for the DHW instead of using traditional water heater technology.

The chiller operating strategy indicates whether the chiller should run or stop. This research uses the full storage strategy, which can cover the main cooling demand of the building (Figure 4.17). The chiller is mainly operated during the day when the energy supply from solar energy is available to make the ice and store in the tank during the day. The main cooling demand is covered by the melting ice and the variation of cooling load is met by the chiller as shown in the Eq. (4.2) (Maccraken, 2013; TRANE, 2009; Naguib, 2006; Simmonds, 1993).

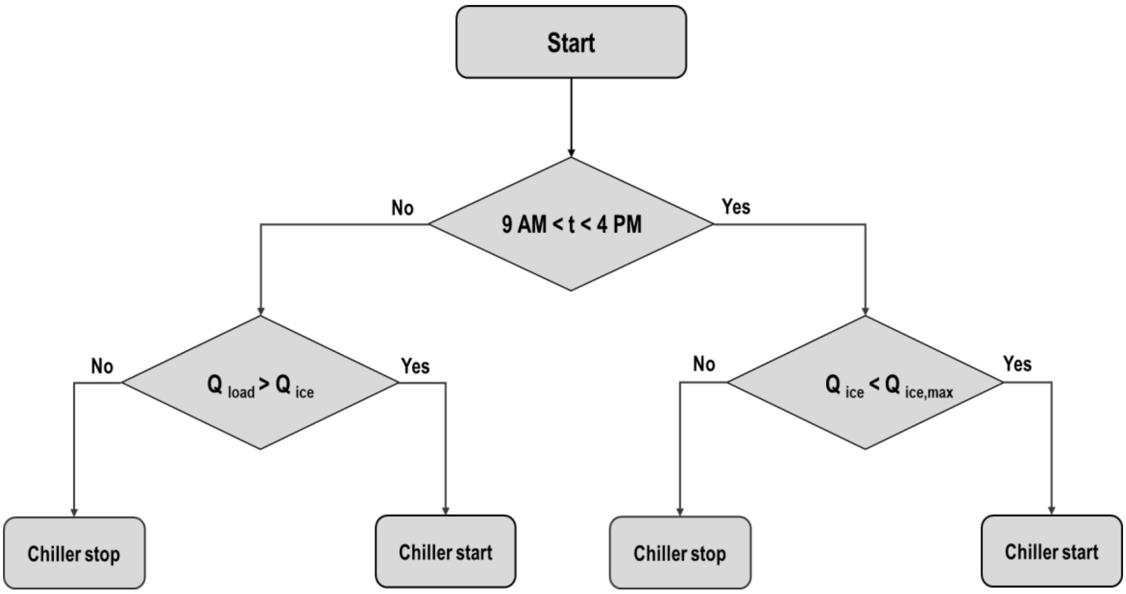


Figure 4.17 Chiller running control strategy flowchart

$$Q_{load} = Q_{ice} + Q_{chiller};\ Q_{ice} < Q_{ice,max} \qquad \text{(Eq. 4.2)}$$

where:

$Q_{ice,max}$	: maximum cooling energy supply of ITES (kWh)
Q_{ice}	: cooling energy supply from ice melt (kWh)
$Q_{chiller}$	: cooling energy supply from the chiller (kWh)
Q_{load}	: cooling energy for load (kWh)

In this research, the maximum ice storage capacity is 70 kWh and the coefficient of performance (COP) of the chiller is estimated at 3.4 (STIEBEL, 2016). This study assumes energy loss through the pipe of 5.6 W/m and from the storage tank of 9.4 W/m^2. (DGNB, 2012). The surplus electricity generated by the PV also supplies the electric appliances during the daytime, and the national grid is an electricity source that supplies electricity to the appliances at night.

4.7.4 GridPVBES scenario

This scenario represents the building with the 5 kWp of PV and battery energy storage (BES) of 14 kWh (TESLA, 2017). The battery capacity in the commercial scale varies between 4 to 16 kWh. The energy demand is the same as the Grid scenario. The cooling and domestic hot water technologies are the same with the Grid and the GridPV scenario.

The energy supply for this scenario is from the national electricity grid and the PV system. The BES stores the excess electricity from the PV during the day and provides electricity to the building when demand occurs. The remaining electricity demand is provided by the national electricity grid (Figure 4.18).

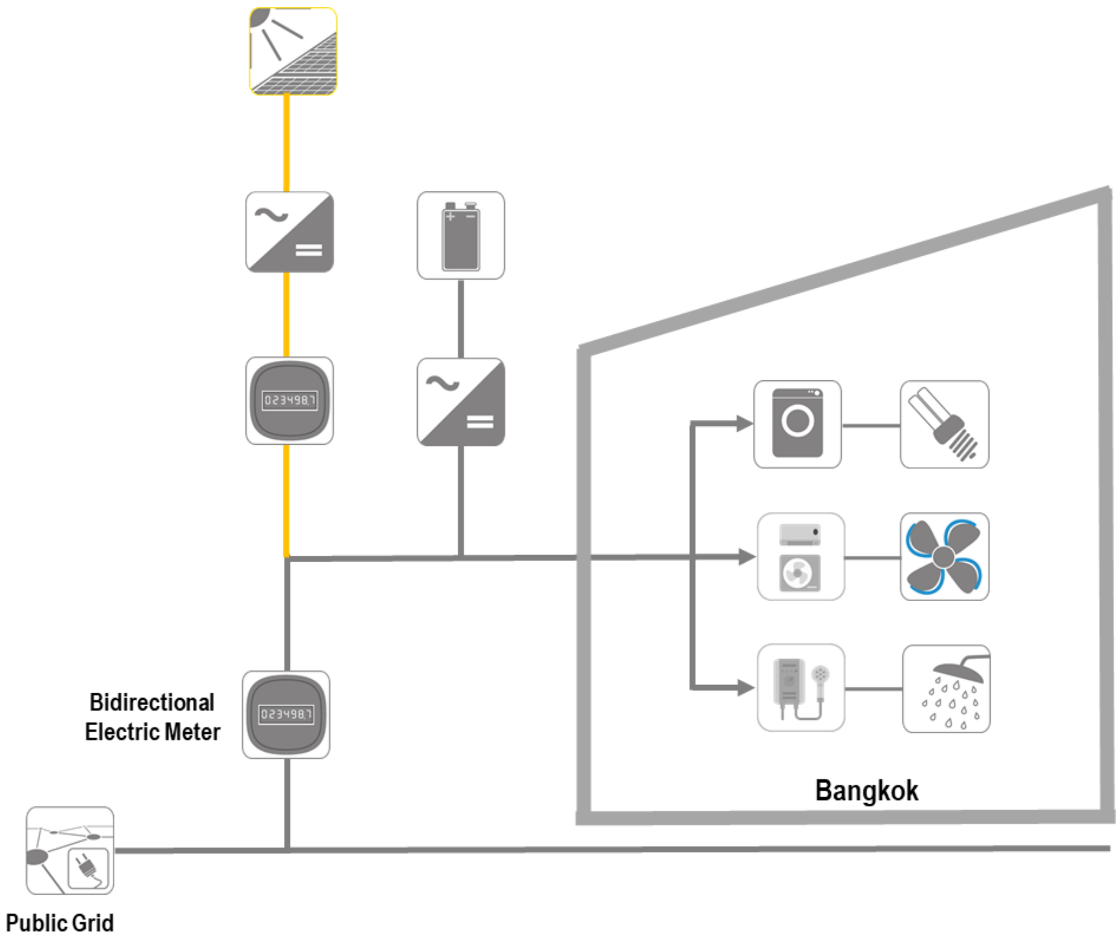


Figure 4.18 Energy concept of GridPVBES scenario

The battery charging/discharging control strategy mainly focuses on providing energy to the building in correlation with the PV generation and the state of charge (SOC) of the battery. The battery can be discharged when the load demand is higher than the energy generation from the PV system and the SOC is higher than the minimum limit of the SOC (SOC_{min}) (Figure 4.19). In other words, the battery will stop discharging when the SOC is lower than the SOC_{min} and the remaining energy demand in the building will be supplied by the national electricity grid.

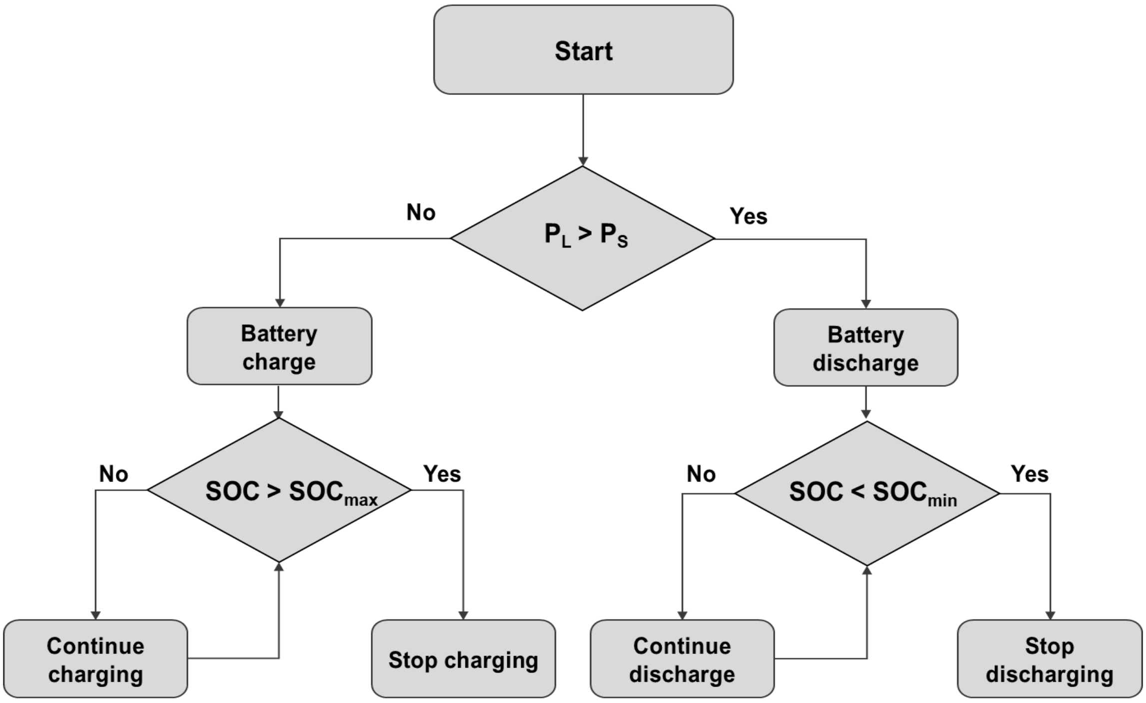


Figure 4.19 Battery charging and discharging control strategy flow chart

In the latter case, the battery is charged when the energy demand is lower than the energy generation from the PV system (if it is available) and the SOC is lower than the maximum limit of the SOC (SOC_{max}) as shown in Eq. (4.3). The battery will stop charging when the SOC is higher than the SOC_{max}. The roundtrip efficiency is assumed at 90%, which is optimistic according to the TESLA datasheet (Tesla, 2017; MDPI 2016).

$$SOC_{min} = 0; SOC_{max} = 1 \qquad \text{(Eq. 4.3)}$$

where:

P_L	: energy demand of building (kWh)
P_S	: energy generation from PV (kWh)
SOC	: state of charge
SOC_{min}	: a minimum limit on the stage of charge
SOC_{max}	: a maximum limit on the stage of charge

4.8 Annual energy balance assessment

The building types and the energy concept scenarios as mentioned in Section 4.3 to Section 4.6 are simulated by using TRNSYS software to examine the annual energy balance in time steps of 15 minutes. The result of each scenario is described below.

4.8.1 Grid scenario

The REF and nZEB buildings are simulated according to the energy concept of the Grid scenario. It shows that the annual electricity consumption of the REF building is 111 kWh/(m^{2}a), while the nZEB building uses 71 kWh/(m^{2}a) (Figure 4.20).

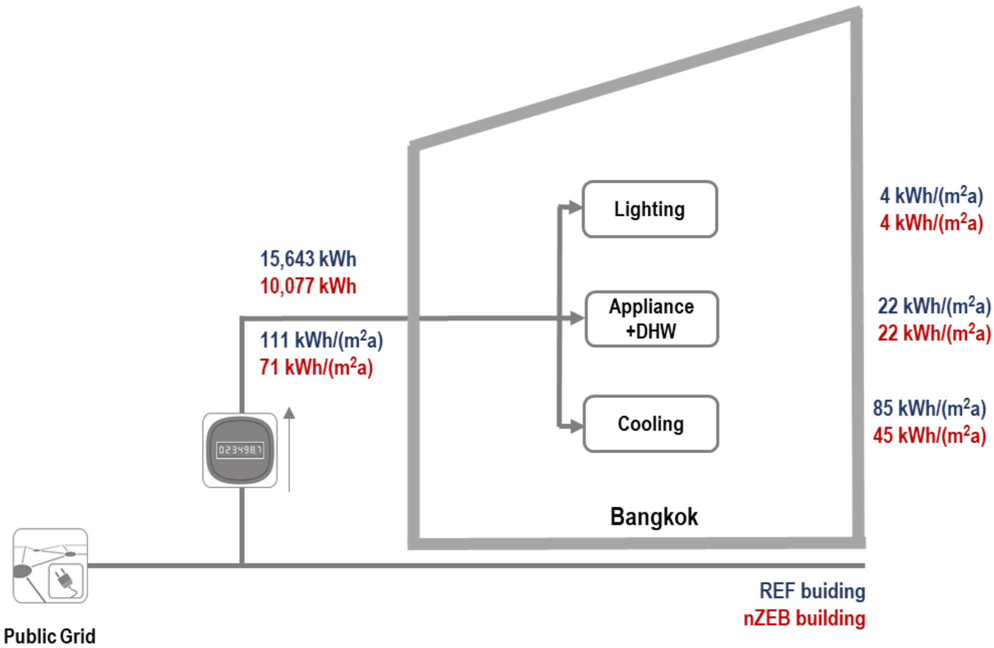


Figure 4.20 Annual electricity balance of the Grid scenario

The advantage of energy efficiency measures through insulation, double glazing windows, and external shading reduce the energy demand by 36% in the nZEB building. The cooling demand is the major electricity consumption of the building, which accounts for 76% of total electricity demand in the REF building (Figure 4.21). The lighting demand is 4 kWh/(m^{2}a), and the household appliances consume 22 kWh/(m^{2}a) in both building cases.

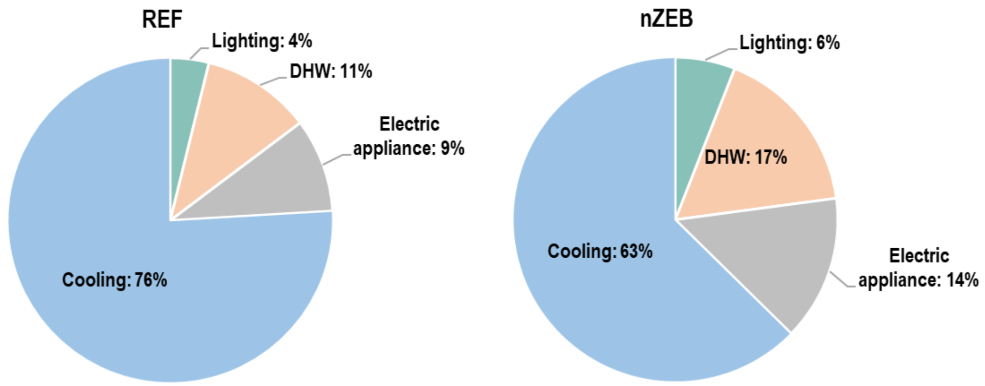


Figure 4.21 Share of electricity demand of REF and nZEB buildings of the Grid scenario

4.8.2 GridPV scenario

The share of electricity demand in the REF and nZEB buildings of the GridPV is the same share as the Grid scenario. The difference between the Grid and the GridPV scenario is the PV system integration. The annual PV generation is 6,307 kWh/a (1,261 kWh/kWp). As a result, the REF and the nZEB building under the GridPV scenario can reduce the imported electricity from the national electrical grid by 12% and 14%, respectively. The excess PV generation is fed into the grid of 4,352 kWh/a from the REF building and 4,905 kWh/a from the nZEB building due to the absence of the energy storage (Figure 4.22). The buildings under this scenario import more electricity than they export to the grid.

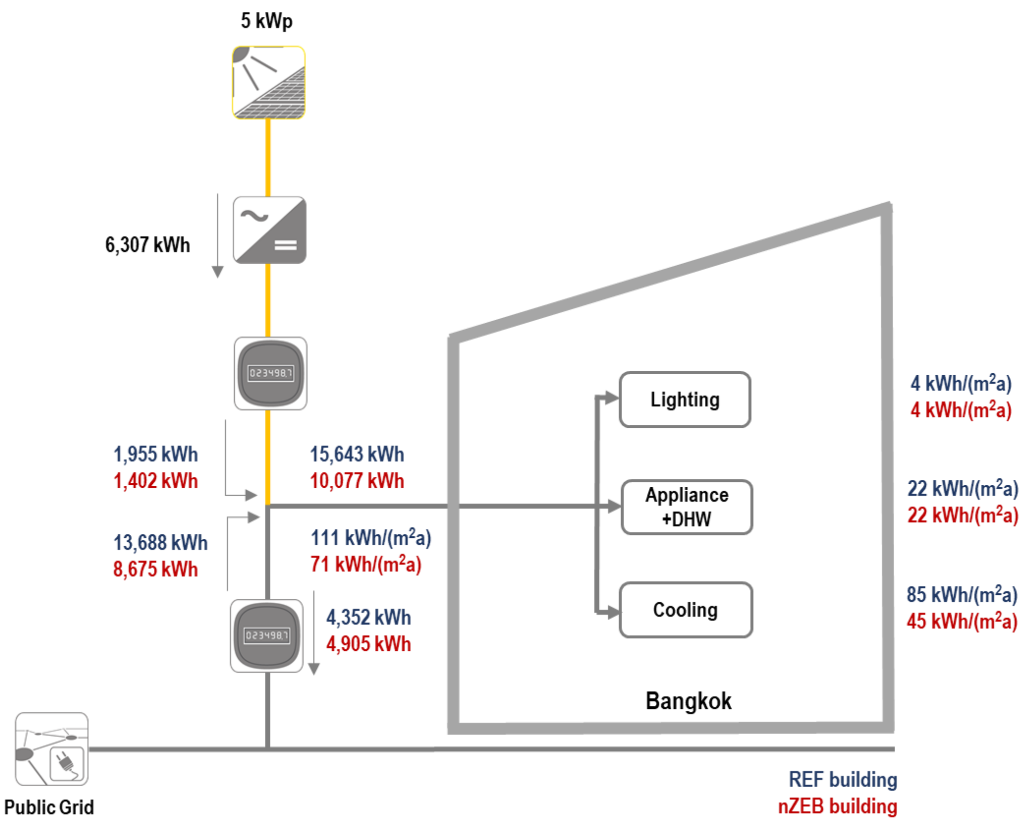


Figure 4.22 Annual electricity balance of the GridPV scenario

The solar fraction is defined as energy provided by the PV system divided by total energy demand of the building, while the term of the PV direct use represents energy provided by the PV system divided by total PV generation. The REF building of the GridPV scenario has a solar fraction of 13%, and a PV direct use of 31%, while the nZEB building has a solar fraction of 14% and a PV direct use of 22% (Table 4.2).

Table 4.2 Solar fraction and PV direct use of GridPV scenario

Building Type	**REF**	**nZEB**
Solar fraction	13%	14%
PV direct use	31%	22%

The REF and nZEB buildings under the GridPV scenario would require a PV capacity of 12.5 kWp and 10 kWp, respectively, to become EnergyPLUS, where the amount of exported energy is higher than the imported energy (Figure 4.23). However, the roof size of the residential building is 89 m^2 which limits the PV panels up to 10 kW. Increasing the PV capacity for the REF building in Thailand cannot achieve the EnergyPLUS standard due to its high energy consumption. On the other hand, the nZEB building with EEM measure can reach the EnergyPLUS standard by increasing the PV capacity up to 10 kWp.

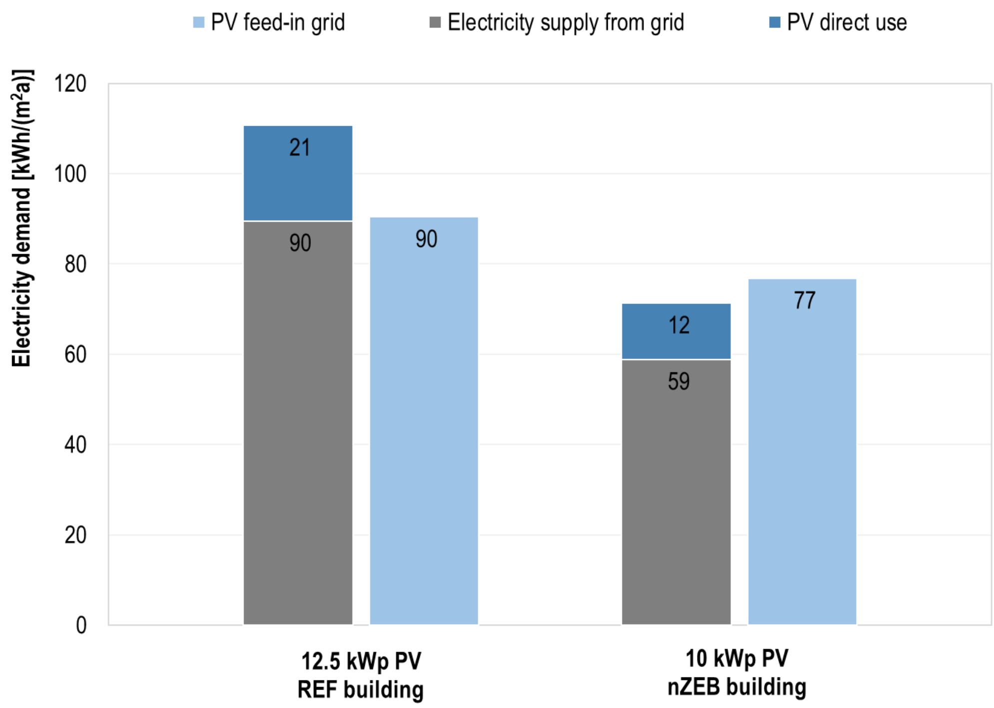


Figure 4.23 Energy performance of the GridPV toward the EnergyPLUS standard

4.8.3 GridPVITES scenario

The annual electricity demand of the REF building is 55 kWh/(m²a) and 37 kWh/(m²a) for the nZEB building (Figure 4.24). As a result, the electricity demand of the GridPVITES is 50% lower than the Grid scenario for the REF building.

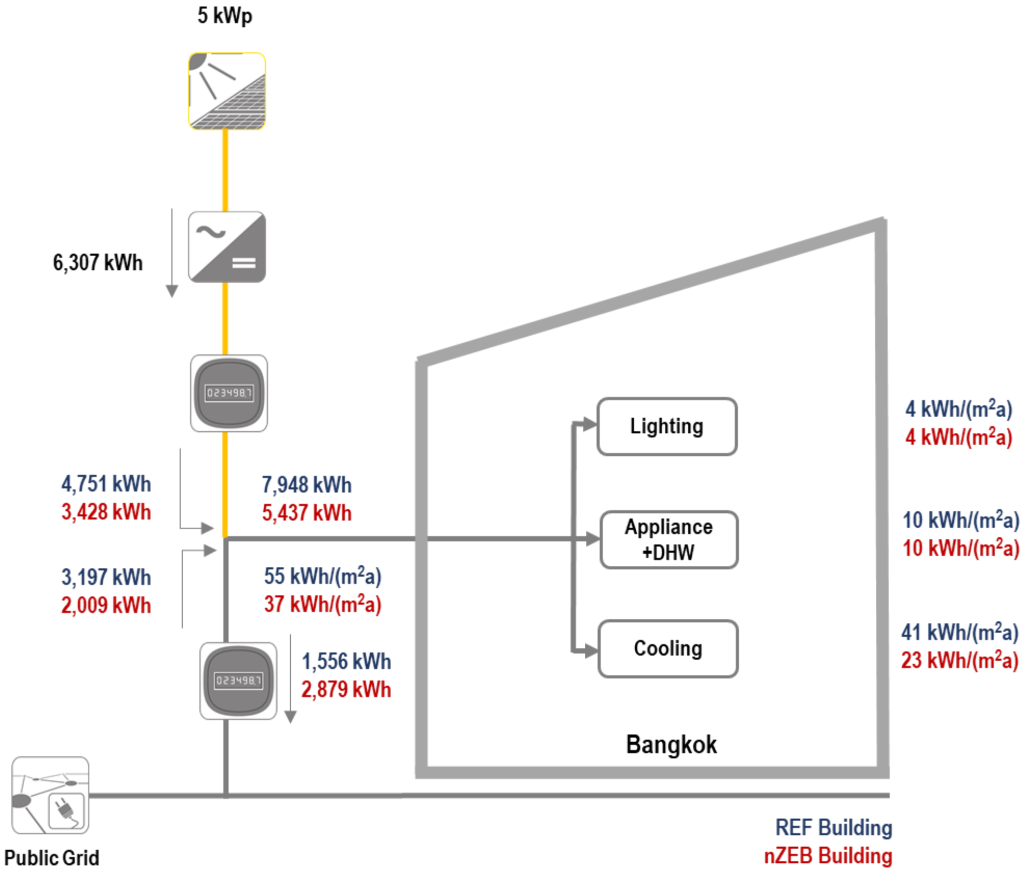


Figure 4.24 Annual electricity balance of the GridPVITES scenario

The share of the electricity demand of the REF and nZEB buildings of the GridPVITES scenario is shown in Figure 4.25. The advantage of the ice thermal energy storage is supplying the cooling energy in the building rather than using electricity from national grid to supply the air conditioning system in the Grid scenario. The cooling energy of the GridPVITES is supplied by the PV generation by making ice in the storage tank during the daytime and delivering energy to the building at night by melting the ice in the storage tank. Moreover, the waste heat can also provide the domestic hot water in the bathroom of the master bedroom.

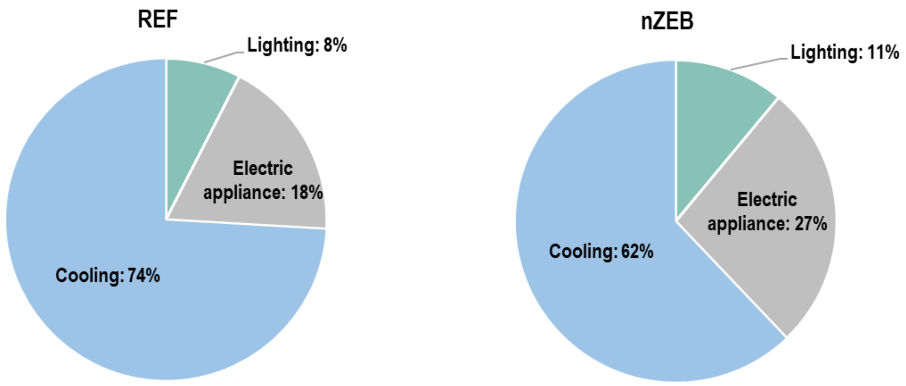


Figure 4.25 Share of electricity demand of REF and nZEB buildings of the GridPVITES scenario

The PV direct use of the GridPVITES scenario is 4,751 kWh/a or 34 kWh/(m^2a), and 3,428 kWh/a or 24 kWh/(m^2a) for the REF and the nZEB buildings, respectively (Figure 4.26).

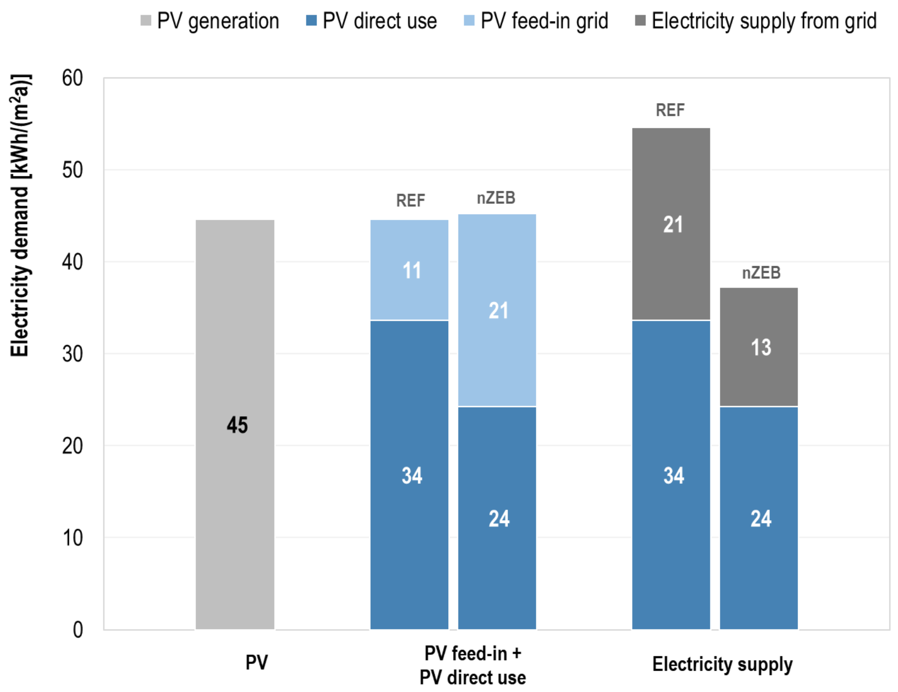


Figure 4.26 PV direct use comparison between the REF building and the nZEB building of the GridPVITES scenarios

The solar fraction is 60% for the REF building and 63% for the nZEB (Table 4.3). Overall, the GridPVITES scenario has a PV direct use greater than the GridPV scenario, at approximately 143% in the REF building. The great advantage of the energy storage system is increasing the PV direct use in the building and reducing the amount of imported electricity from the electricity grid.

Table 4.3 Solar fraction and PV direct use of GridPVITES scenario

Building Type	REF	nZEB
Solar fraction	60%	63%
PV direct use	75%	54%

The nZEB building of the GridPVITES scenario is considered as the EnergyPLUS building where the amount of exported electricity is higher than imported electricity from the grid. The nZEB building of the GridPVITES scenario requires 5 kWp of PV, while the REF building of GridPV requires 12.5 kWp of PV to become the EnergyPLUS standard (Figure 4.27). The integration of ice thermal energy storage and energy efficiency measures (nZEB building in the GridPVITES scenario) can reduce the PV capacity of 7.5 kWp compared to the typical building with integrated PV (REF building in the GridPV scenario) to achieve the EnergyPLUS status.

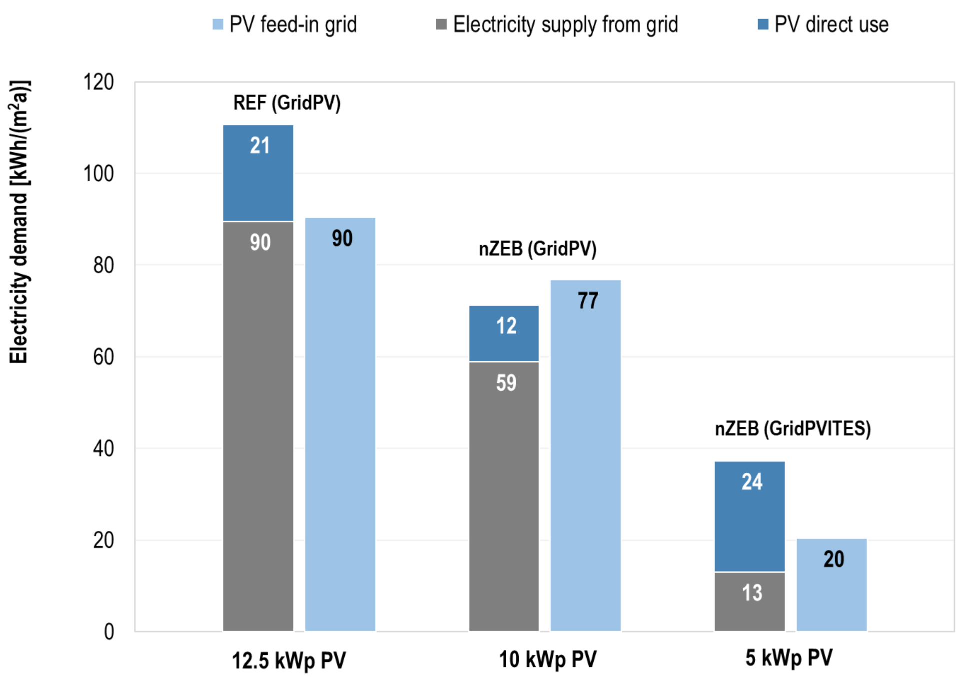


Figure 4.27 Energy performance of the GridPV and GridPVITES toward EnergyPLUS standard

4.8.4 GridPVBES scenario

The annual electricity demand of the REF building is 111 kWh/(m^2a) while the nZEB building is 71 kWh/(m^2a) (Figure 4.28).

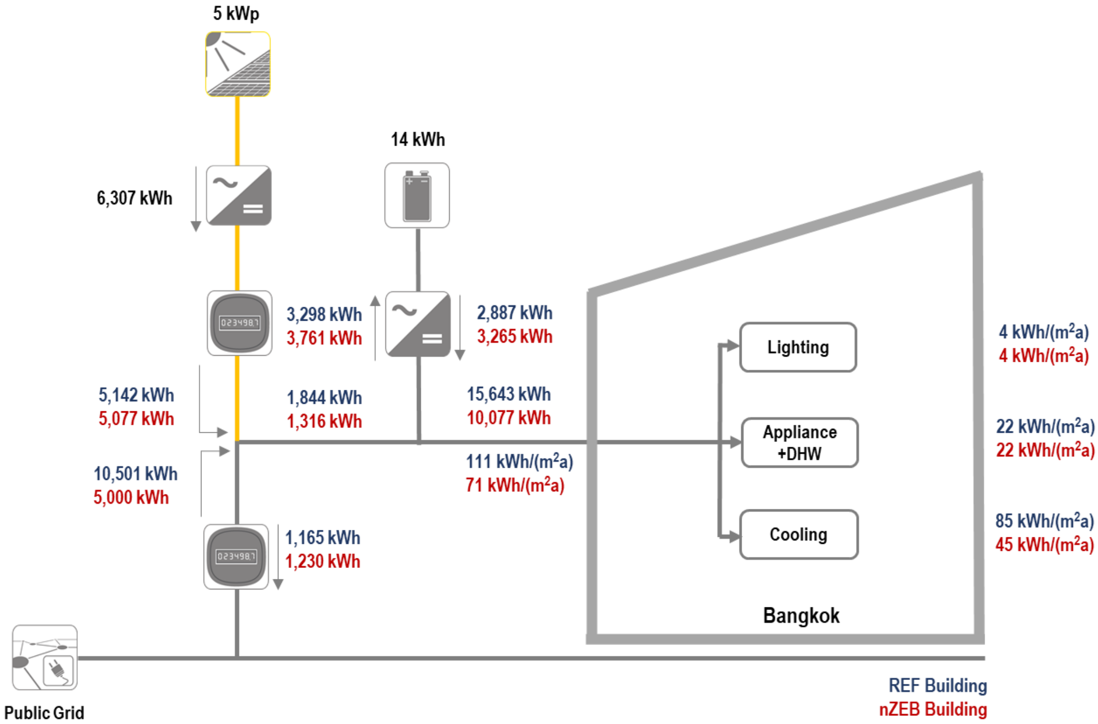


Figure 4.28 Annual electricity balance of GridPVBES scenario

The share of the annual electricity demand of the REF and nZEB buildings is shown in Figure 4.29. The difference is the amount of PV direct use and imported electricity from the national grid network. The BES can increase the PV direct use by 163% compared to the GridPV scenario. The cooling energy demand is the same as the Grid scenario because of the same cooling technology. The battery can discharge 2,887 kWh/a to serve the energy demand of the building until 9 PM, then the national grid must supply the building at approximately of 10,501 kWh/a.

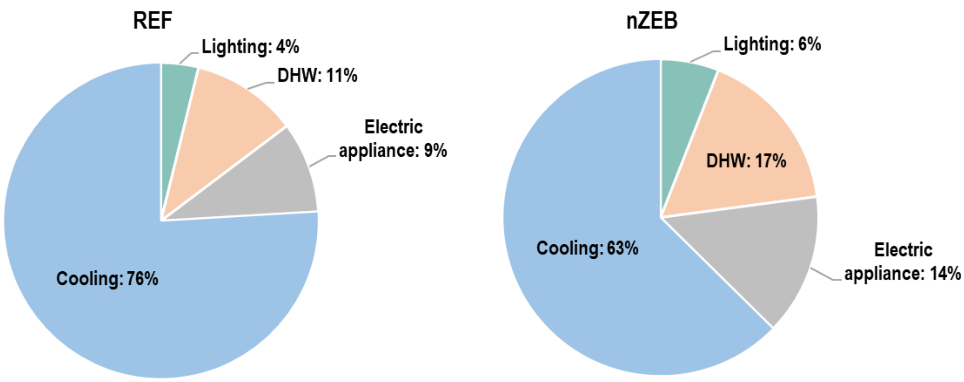


Figure 4.29 Share of electricity demand of REF and nZEB buildings of GridPVBES scenario

The total PV direct use of the GridPVBES is 5,142 kWh/a or 36 kWh/(m^2a), which is the sum of the PV direct to load and the PV energy for charging the battery. The solar fraction is 33% and 50% for the REF and nZEB, respectively (Table 4.4).

Table 4.4 Solar fraction and PV direct use of GridPVBES scenario

Building Type	REF	nZEB
Solar fraction	30%	45%
PV direct use	75%	73%

The GridPVBES has a higher PV direct use than the GridPVITES: only 8% for the REF building (Figure 4.30). The battery is almost empty and ready for a recharge from the PV system the next day. Overall, the GridPVITES has a lower electricity demand at almost half of the GridPVBES scenario.

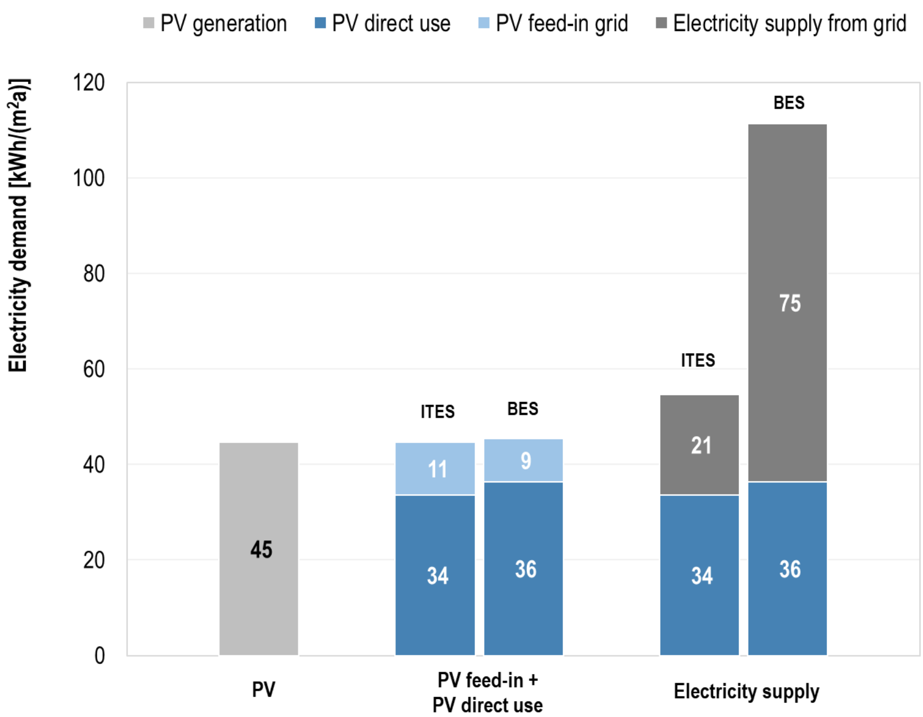


Figure 4.30 PV direct use comparison between GridPVITES and GridPVBES for the REF building

The sensitivity analysis of battery capacity with PV capacity is shown in Figure 4.31.The nZEB building without the battery system has solar fraction of only 14%. Integrating the battery system of 14 kWh with 5 kWp of PV increases the solar fraction from 14% up to 45%. Conversely, if the nZEB building remains with a PV capacity of 5 kWp but increases only the battery capacity from 14 kWh to 52 kWh, the solar fraction only increases from 45% to 50%.

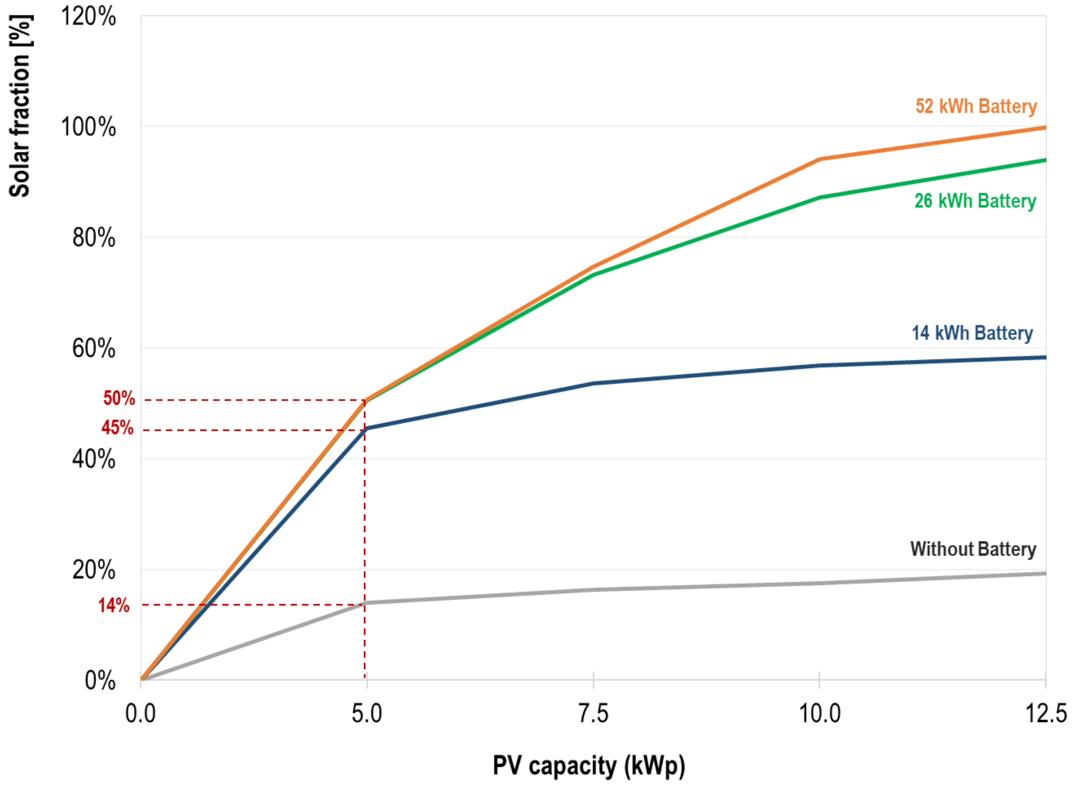


Figure 4.31 Battery capacity sensitivity analysis of the GridPVBES scenario for the nZEB building

Optimizing PV and battery capacity is essential. The larger the battery and PV systems are, the higher the solar fraction. If the nZEB building increases both the PV capacity of 12.5 kWp with the battery system of 52 kWh, it can become nearly 100% of solar fraction. In other words, the nZEB building is nearly 100% supplied by PV system. However, the high battery energy storage system cost and its lifetime are still a crucial concern for investing to provide cooling energy in a detached single-family house.

4.9 Primary energy consumption comparison

The primary energy factor (PEF) for the Thai electricity system in 2017 was 2.5. This is because Thai's power generation is dependent on natural gas as the primary energy source, at approximately 60% of total electricity generation, followed by coal (18%), imported (12%), renewable energy (7%), and others (3%) (EPPO, 2017a). The amount of electricity demand from the electricity grid is converted to primary energy by using the PEF factor as mentioned in Section 4.6.

The REF building in the Grid scenario has the highest primary energy demand of 277 kWh/(m^{2}a) because of the reliance on the electricity grid network without energy efficiency measures for thermal properties improvement (Figure 4.32). The GridPVITES has the lowest primary energy demand at 36 kWh/(m^{2}a) for the nZEB building, or 87% lower than the Grid scenario. The nZEB buiding in the GridPVBES has a primary energy demand of 88 kWh/(m^{2}a), or 68% lower than the REF building in the Grid scenario.

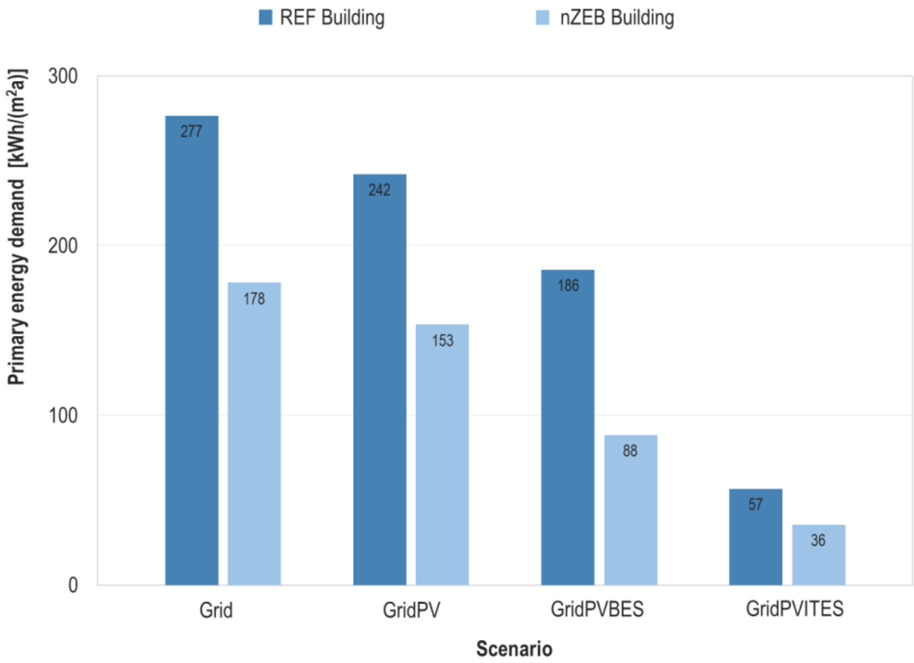


Figure 4.32 Comparison of primary energy demand between scenarios

The ice thermal energy storage system increases PV direct use, which results in less imported electricity demand from the national electricity grid network. The GridPVITES has a primary energy surplus of 15 kWh/(m^2a), while the GridPV has a primary energy deficit of 66 kWh/(m^2a) (Figure 4.33). In other words, the GridPVITES is the EnergyPLUS building where the amount of feed-in to the grid is higher than the amount of electricity supply from the grid.

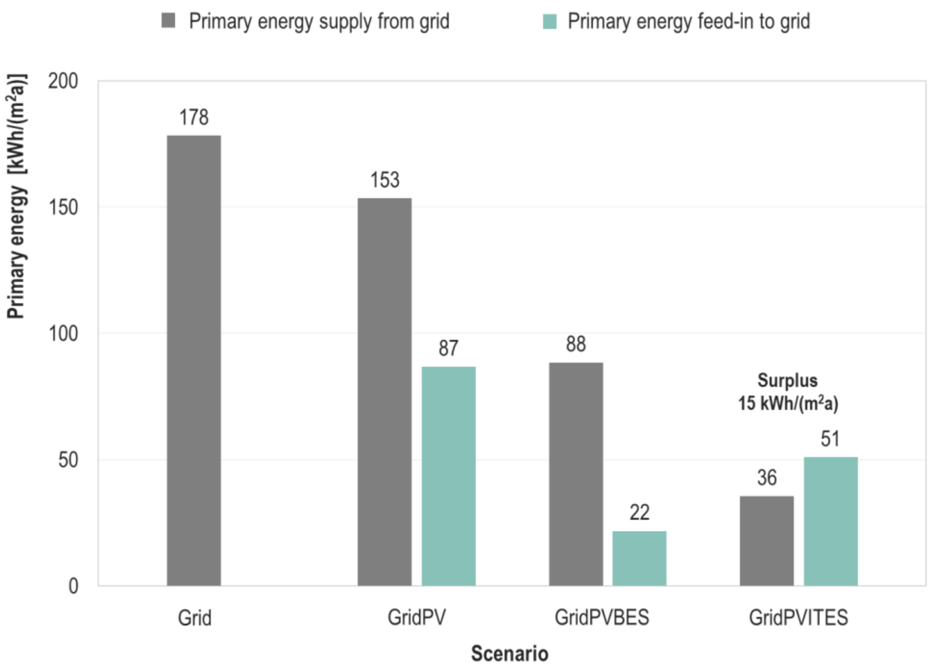


Figure 4.33 Comparison of surplus primary energy of the nZEB building between scenarios

4.10 Carbon dioxide emissions

The Thailand electricity generation system relies on fossil fuels, especially natural gas, as the carbon dioxide emissions from electricity generation in 2017 were approximately 477 grams of CO_2 per kWh, while Germany emitted approximately 461 grams of CO_2 per kWh. The REF building in the Grid scenario emits the highest carbon dioxide emissions of 55 kg of $CO_2/(m^2a)$, while the nZEB building of the GridPVITES emits the lowest carbon dioxide emissions of 7 kg of $CO_2/(m^2a)$, or lower than the REF of the Grid scenario by 87% (Figure 4.34).

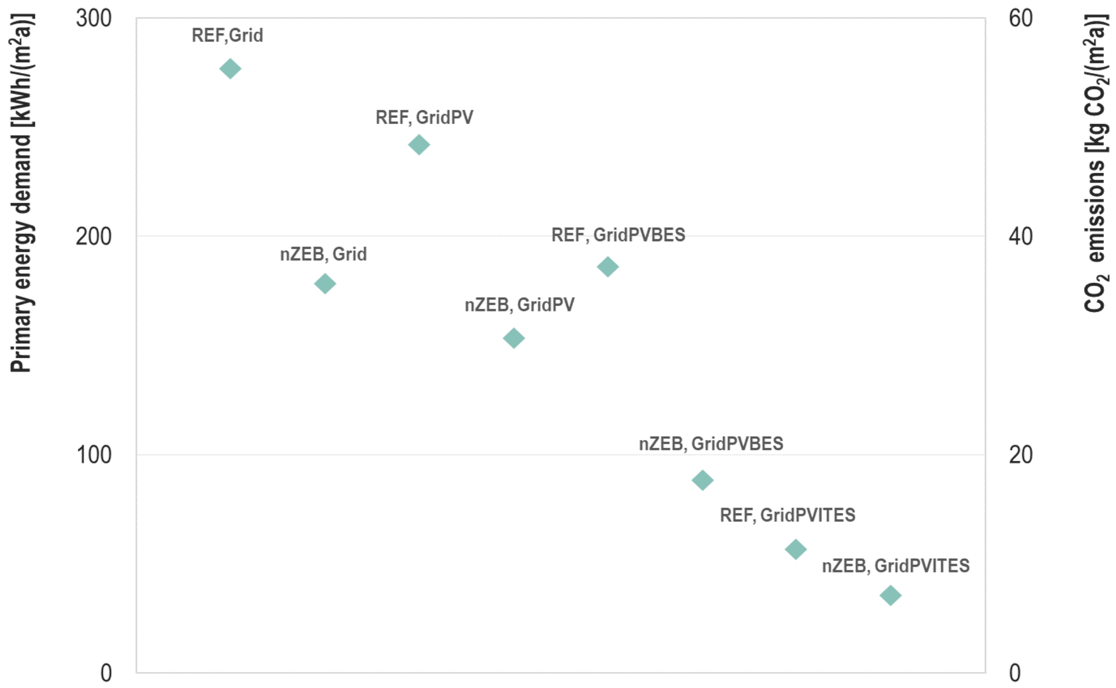


Figure 4.34 Annual CO_2 emissions for each scenario

The life cycle CO_2 emissions can illustrate the environmental impact for the lifetime of the building operation. Generally, the life cycle emissions include the processes of manufacturing, construction, operating, maintenance, and end of life. The operating phase emits the highest CO_2 emissions for the building's lifetime (Iqbal et al., 2017; Kumanayake et al., 2018; Surahman et al., 2015). This research only takes the building operation phase for the CO_2 emissions calculation by assuming a life cycle of 50 years.

The REF building of the GridPV scenario emits CO_2 at approximately 55 kg $CO_2/(m^2a)$ while the PV system of 5 kWp can offset the CO_2 emissions of 22 kg $CO_2/(m^2a)$, therefore it has a minus CO_2 offset of 33 kg $CO_2/(m^2a)$. The nZEB building with the battery energy storage system of 14 kWh emits CO_2 emissions of 20 kg $CO_2/(m^2a)$ lower than the REF building without the battery system. However, the nZEB building with the battery system still cannot compensate the overall CO_2 emissions of the building; it has a minus CO_2 offset of 13 kg $CO_2/(m^2a)$. The nZEB building with the ice thermal energy storage system has a positive CO_2 offset of 3 kg $CO_2/(m^2a)$ because the amount of clean energy from the PV system is higher than the energy demand of the building (Figure 4.35).

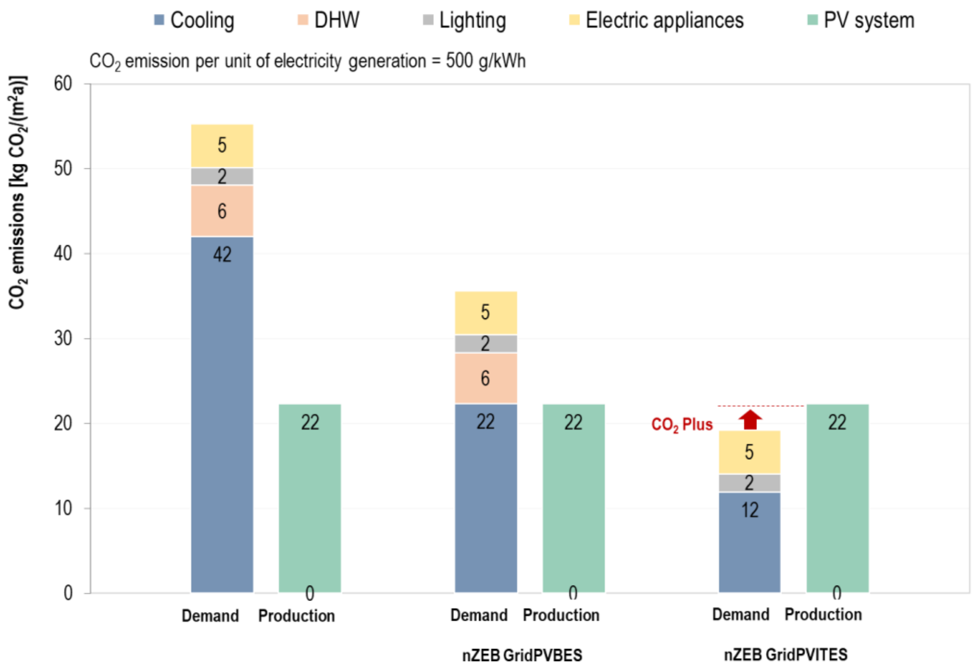


Figure 4.35 CO_2 emissions comparison between scenarios

Taking the life cycle emissions into calculation, the accumulative carbon dioxide emissions of the nZEB building in the GridPVITES scenario has an overall CO_2 offset of approximately 22 tonnes of CO_2, while the REF building of the GridPV scenario emits 255 tonnes of CO_2 by the end of its life cycle (Figure 4.36). The nZEB building in GridPVITES can compensate the carbon dioxide emissions from its operation because the life cycle CO_2 savings are greater than the CO_2 emissions. The energy design concept with high potential integrated technology in the building does not only reduce energy consumption, but beyond it can improve the environment.

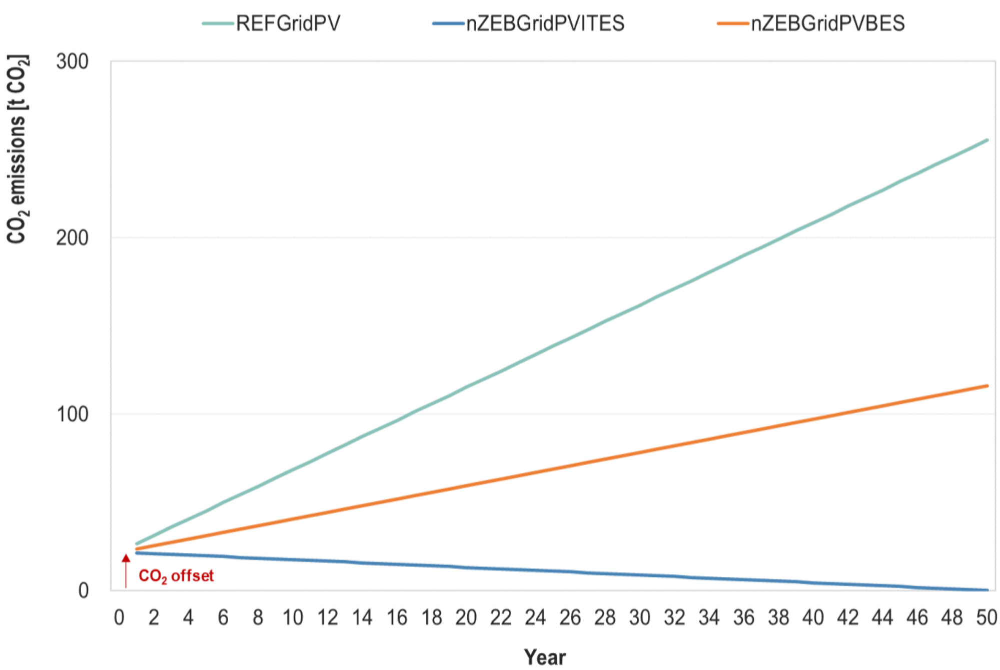


Figure 4.36 CO_2 offset of the GridPVITES scenario

4.11 Conclusion

The detached single-family house represents a major residential building in Thailand. The split type air-conditioning (AC) system is a common cooling technology in a typical detached family house. Cooling energy is the main energy demand in the building. The cluster PV on the roof is becoming attractive for residential buildings due to the rapidly decreasing investment costs and the abundance of solar irradiation in Thailand. The common prosumer usually installs the PV on the roof without reducing the energy demand in the building. The mismatch between PV generation and energy demand in the residential building becomes a crucial concern for the distribution system operator due to the high amount of reversed power flow from the PV system into the low voltage electricity grid network.

Selecting proper integrated technology can mitigate the problem mentioned above. It was found that energy efficiency measures (EEM) are essential for residential buildings in Thailand. Table 4.5 shows the summary of energy performance and CO_2 emissions of each scenario. Deploying the EEM in the nearly zero energy building (nZEB in the Grid scenario) requires 27% less imported electricity than installing only the PV system on the roof (REF in the GridPV scenario). The building with a combination of EEM technology and a PV system (the nZEB building in GridPV) can decrease imported electricity even more by 37% compared to the reference (REF) building in the Grid PV scenario. In addition, the nZEB building with the PV system can achieve the EnergyPLUS standard by increasing the PV capacity up to 10 kWp.

The battery energy storage (BES) system is a well-known energy storage application for the household. The integration of 14 kWh of the battery capacity and 5 kWp of the PV system can increase solar fraction from 13% to 30% for the REF building. Even though the battery system can increase the solar fraction, the total electricity demand of the building remains the same because the building still imports electricity from the national grid of 75 kWh/(m^2a) for the cooling demand after the full battery discharge.

Table 4.5 Summary of energy performance and CO_2 emissions of each scenario

Scenario	**Grid**		**GridPV**		**GridPVITES**		**GridPVBES**	
Building Type	**REF**	**nZEB**	**REF**	**nZEB**	**REF**	**nZEB**	**REF**	**nZEB**
Electricity demand [kWh/(m^2a)]	111	71	111	71	55	37	111	71
Imported Electricity [kWh/(m^2a)]	111	71	97	61	21	13	75	35
Solar fraction (%)	0%	0%	13%	14%	60%	63%	30%	45%
CO_2 emissions [kg of CO_2/(m^2a)]	55	36	48	31	11	7	37	18

The ice thermal energy storage (ITES) offers an advanced energy design concept by considering the ITES system's potential to provide cooling energy to the building. Moreover, waste heat can also generate the domestic hot water for the building. A building with the EEM and ITES systems (nZEB building in the GridPVITES scenario) can reduce imported electricity by 63% compared to the BES case (nZEB building in GridPVBES scenario). Moreover, the nZEB building with the 5 kWp PV and the ITES system can achieve the EnergyPLUS concept, in which the amount of exported primary energy is higher than imported primary energy.

The energy design concept is very essential for a detached single-family house in Thailand. A building with a PV system only cannot decrease the energy demand of the building; the building still requires electricity from the national electricity grid. This is because of the mismatch between energy demand and PV generation; energy demand occurs at night while the PV system generates electricity during the daytime. Energy efficiency measures can decrease the energy demand of the building while the PV system can generate clean electricity for the building. The building with the energy storage system can increase solar fraction compared to the building without the energy storage system. The most remarkable advantage of the ITES and EEM integration in the building goes beyond the energy saving target in the building - it can compensate for the carbon dioxide emissions at the end of a life cycle compared to other integrated technology applications.

Chapter 5

Assessment of Power Quality of High PV Integration in a Low Voltage (LV) Network

5.1 Introduction

The smart grid incorporates the residential prosumer into the energy system by integrating smart technology components to provide effective control. The single small PV system in the LV network does not cause a power quality problem, but high PV capacity is becoming a crucial concern for the distribution system operator (DSO). Some existing LV networks may not be able to support high PV generation. The oversizing of PV capacity and the mismatch between PV generation and energy demand in the residential building cause power quality concerns in the LV network such as voltage rise and electrical infrastructure overload.

This chapter presents the investigation into power quality impacts from high PV generation in a low voltage network. The conservative PV hosting capacity limitation of up to 15% of the distributed transformer (DTR) is investigated in this research to examine whether the LV network can handle higher PV penetration by taking the technical potential of the prosumer into account. Active voltage control strategies for a high PV penetration are recommended for the future grid code revision for Thailand.

5.2 Power quality concerns in LV system with high PV penetration

There are several power quality issues regarding the clustered PV in a low voltage LV network. This research focuses on three issues: harmonics, voltage rise, and reactive power control.

5.2.1 Harmonics

Harmonics are usually produced by a nonlinear load (e.g. inverter, motor, printer, TV, electronic lighting ballast) which causes sinusoidal waveform distortion (Figure 5.1).

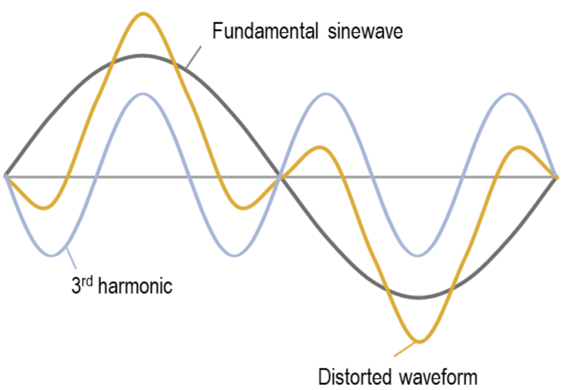


Figure 5.1 Distorted sinusoidal waveform

The nonlinear load influences the current harmonics directly and the voltage harmonics through system impedance, which distorts the voltage waveform. The equipment in the system or the nearby system may experience interference from the harmonics, such as overloading from the additional current and voltage, increasing heating of the transformer, overstressing of the capacity bank, and interference with telecommunications lines (Fekete et al., 2012). The PV inverter is considered as nonlinear equipment which may affect the current harmonics and voltage harmonics in the distribution system (Shivashankar et al., 2016).

The total harmonics distortion (THD) index is used to describe the total signal distortion, which is a fraction of all harmonic components to the fundamental component (Eq. 5.1). The higher the THD, the poorer the power quality. If the size of the PV system is very small, the harmonics effect can be neglected, but the concern arises for high PV penetration integration in a low voltage network without harmonic emission restrictions of the PV inverter system.

$$THD_i=\sqrt{\sum_{n=2}^{n=n}\left(\frac{I_n}{I_1}\right)^2} \times 100 \qquad \text{(Eq. 5.1)}$$

where:

I_1 : root mean square (rms) value of the fundamental current

n : rms value of the n^{th} harmonic

THD_i : total harmonics distortion of current i

Several studies have found that current harmonics arise in the morning and evening, or when there is a sudden change in clouds called the shading effect (Fekete et al., 2012; Patsalides et al., 2012; Ebad et al., 2016). In other words, solar irradiation has a direct effect on current harmonics (THDi) but not on voltage harmonics (THDu). THDu is strongly dependent on the PV capacity. The higher the PV capacity at the same point of common coupling (PCC), the higher the THDu. According to the IEEE 519-1992, THDu at the PCC in a power system below 69kV is limited to 5% to provide a good quality of voltage to the consumer. Topology and PV capacity can affect the power quality concern in the LV network (Toobpae & Sudta, 2015; Patsalides et al., 2012; Tonkoski, 2012; Ebad et al., 2016).

5.2.2 Voltage rise

The voltage rise problem is becoming a more serious issue for high PV penetration in a low voltage network. Generally, the voltage drop occurs along the feeder because of line impedance (Figure 5.2). The line impedance consists of a real component (R) and an imaginary component (X) (Eq. 5.2).

$$V_r = V_s - I(R+jX) \qquad \text{Eq. (5.2)}$$

where:

V_s : supply voltage (volt)

V_r : load voltage (volt)

I : current (ampere)

R : resistance (ohm)

X : inductive reactance (ohm)

j : imaginary unit

The longer the feeder, the higher the impedance. Therefore, the transformer has to supply a higher current to deliver the same amount of power, which results in higher transformer capacity and investment costs.

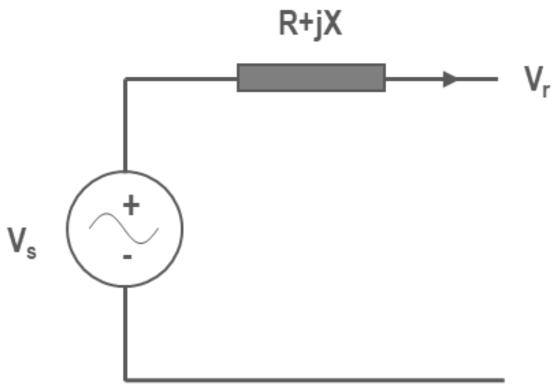


Figure 5.2 Equivalent circuit of feeder (Demirok et al., 2009)

The PV system integration at the end of a long feeder (e.g. rural area) can improve the voltage drop problem during the daytime instead of investing in a larger transformer (Saksornchai et al., 2015; Demirok et al., 2009; Langaard, 2016) (Figure 5.3).

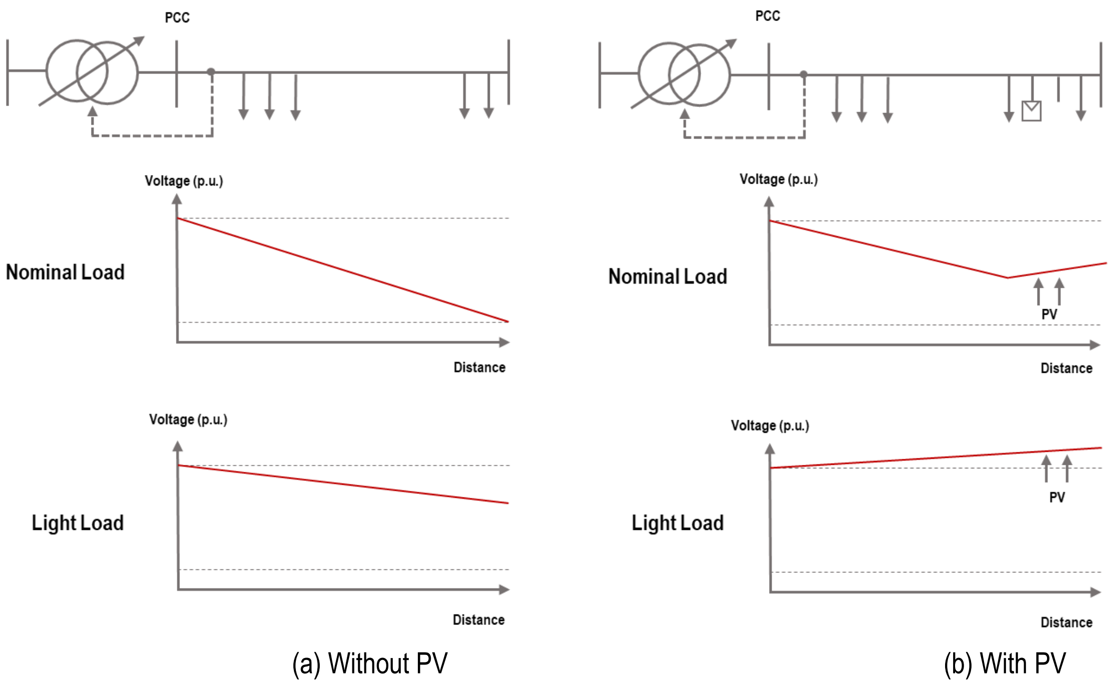


Figure 5.3 Voltage profile with PV and without PV along the feeder (Demirok et al., 2009)

The voltage rise issue depends on the PV capacity, topology, feeder congestion, and the transformer impedance (Tonkoski et al., 2012; Taothong & Tonprom, 2014). The voltage rise effect from a single PV capacity in the feeder can be neglected because it is insignificant. But high PV penetration connected in the same feeder can cause a high amount of reverse power flow and raises the voltage level to exceed the standard limit (Alam et al., 2013; Tonkoski et al., 2012). In electrical system analysis, the per unit (p.u.) is a term referring to the actual value compared to the base value as a fraction.

The voltage rise needs to be examined during light load to adjust the on-load tap changer (OLTC) for delivering power at the nominal load (Demirok et al., 2009). The passive control measure can be done by integrating protection components, such as the capacity bank, step voltage regulators (SVR), reactive power controller, increasing the feeder size, and reducing the transformer short-circuit resistance (Apicharsiritham et al., 2015; Tonkoski et al., 2012; Punyachai et al., 2014). The active voltage control measures offer a more flexible approach by allowing the prosumer to provide the reactive power support to the LV network, e.g. adjusting the power factor operating value, integrating the distributed battery energy storage system.

5.2.3 Reactive power

Transferring electric power to the load in an alternating current system does not only consist of real power (P, Watt) but also reactive power (Q, Var). The apparent power (S, VA) is the sum of the real power and reactive power (Eq. 5.3). The power factor is defined as the ratio of real power to apparent power that is flowing in the distribution network to the load (Eq. 5.4).

$$S = \sqrt{P^2 + Q^2} \tag{Eq. 5.3}$$

$$\text{Power Factor (PF)} = \frac{P}{S} \tag{Eq. 5.4}$$

where:

S : apparent power (VA)
P : active power (Watt)
Q : reactive power (VAR)

The power factor (PF) value is between -1 to 1. In reality, the power system consists of a non-linear load which absorbs or generates the reactive power; hence the power factor is less than 1. The terms of leading or lagging power factor indicates the current lead (conductive load) or lag (inductive load) of the voltage (Figure 5.4).

(a) Lagging power factor (b) Leading power factor

Figure 5.4 Power factor in the electrical system (Demirok et al., 2009)

While real power is essential for supplying to the load, reactive power is required to maintain the voltage level. Reactive power becomes a crucial concern for a large amount of the PV in the LV network grid by operating the old-fashion PV system at unity power factor. In other words, the PV system generates higher active power but the reactive power remains the same value in the system. As a result, some feeders might face an overvoltage problem.

In Germany, the PV prosumer with a capacity less than 13.8 kVA is required to operate a PV inverter at the power factor between 0.95 lagging/leading. Those over the capacity of 13.8 kVA must operate the power factor between 0.9 lagging/leading to provide reactive power support (VDE, 2018).

In 2012, the Energieeinsparungsgesetz Energy Saving Act (or called Renewable Energy Resource Act) defines that the PV system with a capacity of less than 30 kWp must limit the active power feed in up to 70% of rated capacity without remote power control by the DSO (EEG, 2012). Another voltage control solution is deploying the energy storage system (ESS) by integrating control strategies, which can limit active power or provide reactive power support to the system (Liu et al., 2012; Rafi et al., 2016; Alam et al., 2013).

5.3 Analysis framework

The main issue of Thailand's preliminary grid code for PV integration is the limiting of the total PV capacity at 15% of distribution transformer (DTR). The restriction of 15% was originated from the California Public Utilities Commission (CPUC) in 1999 and is used as the grid code in several countries, such as India and Thailand, to avoid the problem of reversed power flow (GIZ, 2017). In Germany, instead of using the transformer capacity, the PV inverter is capped at 70% of the rated power with the reactive power supported by the PV inverter.

This chapter aims to assess the power quality impact by increasing the PV capacity to be more than 15% in the urban areas of Bangkok. The analysis framework is shown in Figure 5.5.

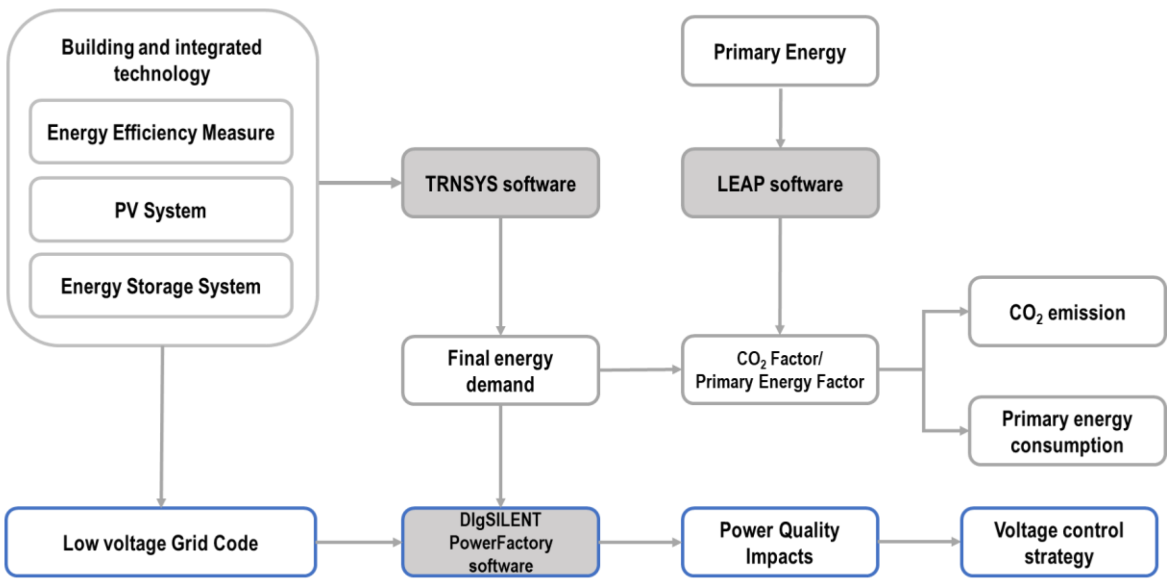


Figure 5.5 Low voltage network analysis framework

The sensitivity analysis of PV penetration is investigated to identify the PV hosting capacity and whether it can be increased more than the grid code restriction. The energy demand and PV generation profile are retrieved from the result in Chapter 4. The electrical equipment parameters are simulated in the DIgSILENT PowerFactory software (Figure 5.6). Finally, voltage control strategies are proposed for the future grid code revision for PV integration in the low voltage network of Thailand.

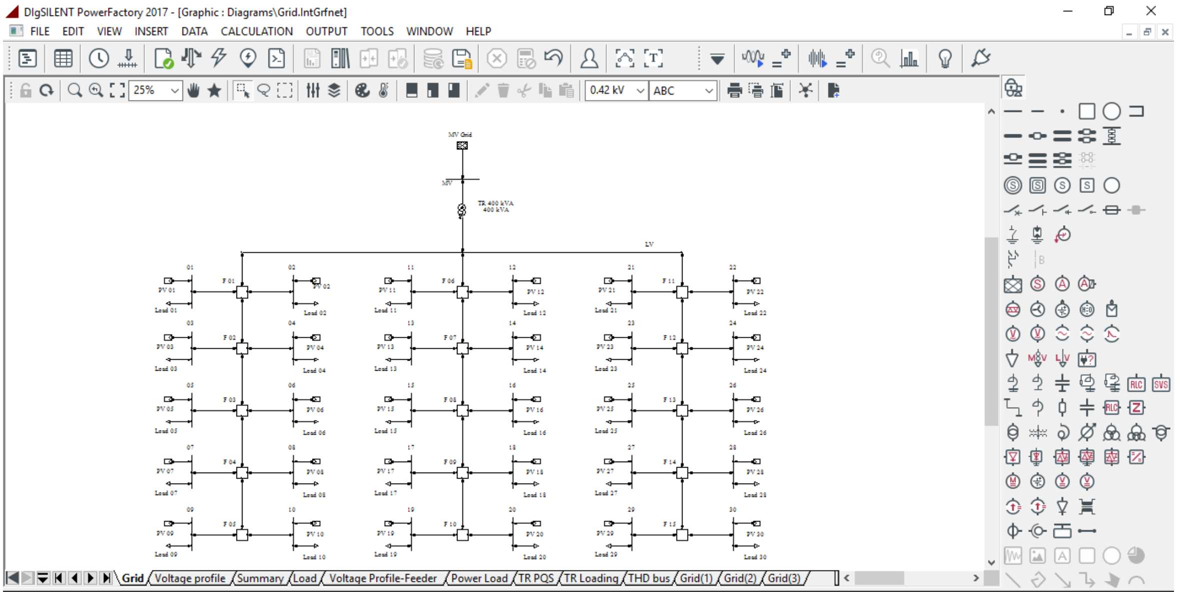


Figure 5.6 Simulation model in the DIgSILENT PowerFactory Software

5.4 Simulation structure

5.4.1 Grid code conditions

The grid code of the Metropolitan Electricity Authority (MEA) is used as the criteria to investigate the power quality problem from high PV integration. According to the MEA grid code of the LV connection, it limits the maximum generator capacity per household at 5 kWp. It also limits the PV penetration at the same transformer at 15% of the DTR (MEA, 2016) (Eq. 5.5).

$$\text{PV penetration (\%)} = \frac{\text{Total PV capacity}}{\text{Transformer capacity}} \text{ x } 100\% \qquad \text{(Eq. 5.5)}$$

Moreover, the MEA grid code also limits the maximum individual PV capacity at 5 kWp when connected to a low voltage network.

1) Total harmonic distortion (THD) limit

This research assumes the THD_i of the PV inverter according to the MEA standard in Table 5.1. The THD_i of the PV inverter must not be over 5% (MEA, 2016). The MEA grid code does not define THD_u, therefore this research applies the IEEE standard (519-1992) for the maximum THD_u at 5% in which an individual harmonic does not exceed 3% of the fundamental harmonics (IEEE, 1922).

Table 5.1 Harmonics current limits according to MEA grid code

Harmonic Order (h)	**Maximum harmonics current in Percent of fundamental frequency current at PCC**
3 ≤ h ≤ 9	4
11 ≤ h ≤ 15	2
17 ≤ h ≤ 21	1.5
23 ≤ h ≤ 33	0.6
h ≥ 35	0.3
THD_i < 5%	

2) Voltage level limit

The MEA grid code defines that the voltage value must be between 0.93 p.u. and 1.03 p.u. for any system connected to the LV network.

3) The mandatory power factor of PV inverter

The MEA grid code specifies the power factor of the PV inverter system at 0.95 leading/lagging. This research assumes the unity power factor (PF=1) as the reference case or business as usual (BAU). The power factor value variation will be assessed for the active voltage control strategies.

5.4.2 Location

This research examines both an existing LV network (Figure 5.7) and a new network (Figure 5.8) in an urban area of Bangkok. The existing LV network represents the existing LV network with various feeder lengths and a rated load, while the new network represents the newly-built LV network for modern residential buildings with a higher rated load.

Figure 5.7 Existing LV network location

Figure 5.8 New LV network location

The existing network consists of 48 residential buildings and the new network has 30 buildings. The feeder length of both the existing and the new LV network is between 0.003-0.120 km. The feeder length and transformer capacity are retrieved from real measurements at the locations in Bangkok, as shown in Table 5.2 and Table 5.3.

Table 5.2 Feeder lengths and rated loads of in existing network

Load No.	Existing network		Load No.	Existing network		Load No.	Existing network	
	Length (km)	Rated Load (kW)		Length (km)	Rated Load (kW)		Length (km)	Rated Load (kW)
1	0.061	3	17	0.081	1	33	0.043	3
2	0.053	1	18	0.072	1	34	0.056	1
3	0.042	1	19	0.061	1	35	0.069	1
4	0.059	1	20	0.048	3	36	0.069	1
5	0.074	7	21	0.028	3	37	0.079	1
6	0.088	3	22	0.038	1	38	0.110	1
7	0.088	1	23	0.074	3	39	0.100	3
8	0.800	1	24	0.085	3	40	0.100	3
9	0.071	3	25	0.110	1	41	0.058	3
10	0.062	3	26	0.110	3	42	0.043	1
11	0.016	1	27	0.069	1	43	0.055	3
12	0.043	1	28	0.056	7	44	0.054	1
13	0.031	1	29	0.041	1	45	0.080	7
14	0.064	1	30	0.033	3	46	0.089	1
15	0.073	3	31	0.008	1	47	0.100	1
16	0.081	3	32	0.005	1	48	0.110	1

Table 5.3 Feeder lengths and rated loads of in new network

Load No.	New network		Load No.	New network		Load No.	New network	
	Length (km)	Rated Load (kW)		Length (km)	Rated Load (kW)		Length (km)	Rated Load (kW)
1	0.054	7	13	0.047	7	25	0.061	7
2	0.038	7	14	0.043	7	26	0.037	7
3	0.093	7	15	0.058	7	27	0.079	7
4	0.057	7	16	0.058	7	28	0.051	7
5	0.110	7	17	0.069	7	29	0.091	7
6	0.100	7	18	0.070	7	30	0.062	7
7	0.120	7	19	0.080	7	31	0.100	7
8	0.096	7	20	0.083	7	32	0.076	7
9	0.120	7	21	0.085	7	33	0.110	7
10	0.100	7	22	0.088	7	34	0.083	7
11	0.015	7	23	0.083	7	35	0.083	7
12	0.003	7	24	0.023	7	36	0.120	7

5.4.3 Low voltage network parameter

Each house is connected to a low voltage feeder which is supplied by the 12 kV/0.4 kV of distribution transformer (Figure 5.9). This study assumes it is balanced for each phase. The transformer capacity in the existing and the new networks is different, as shown in Table 5.4. The distribution transformer delivers the electricity to the main LV feeder line of 50 sq.mm and then to the branch line of 35 sq.mm for the existing network, as shown in Table 5.5. Additionally, Table 5.6 shows the new network has a bigger cross-section line due to the higher transformer capacity.

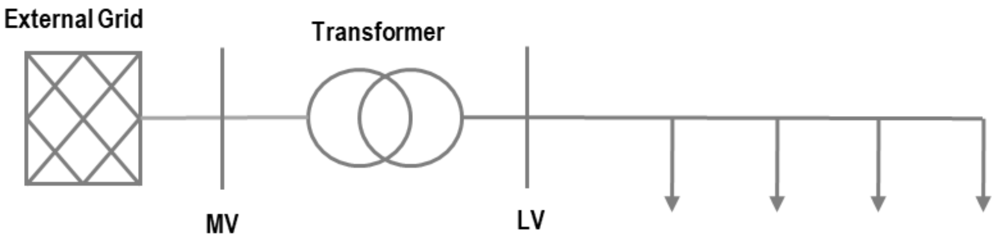


Figure 5.9 LV network simulation with PV

Table 5.4 Transformer parameter

Parameter	Existing network	New network
Rating	250 kVA	400 kVA
Voltage level	12kV/0.4kV	12kV/0.4kV
Vector group	Dyn 11	Dyn 11
% Short circuit	4%	4%
Copper loss	2.95 kW	4.6 kW
No load loss	0.5 kW	0.8 kW

Table 5.5 Line parameter for existing network

Parameter	LV pole-pole line	Branch line
Cross section (sq.mm)	50	25
R (ohm/km)	0.39	0.731
L (mH/km)	0.434	0.48
C (μF/km)	0.249	0.203

Table 5.6 Line parameter for new network

Parameter	LV pole-pole line	Branch line
Cross section (sq.mm)	95	35
R (ohm/km)	0.197	0.529
L (mH/km)	0.391	0.455
C (μF/km)	0.315	0.225

5.4.4 PV generation and load profile

The load pattern of the new and existing buildings is the same but only the rated load is different. The load profile is divided into weekday and weekend where the holidays are assumed to have the same load profile as the weekend. The peak load occurs at night when all occupants are at home. During the day on weekdays, the load demand is nearly zero, which consists of standby power for the electric appliances (Figure 5.10). The mismatch between load demand and PV generation can be seen clearly on weekdays.

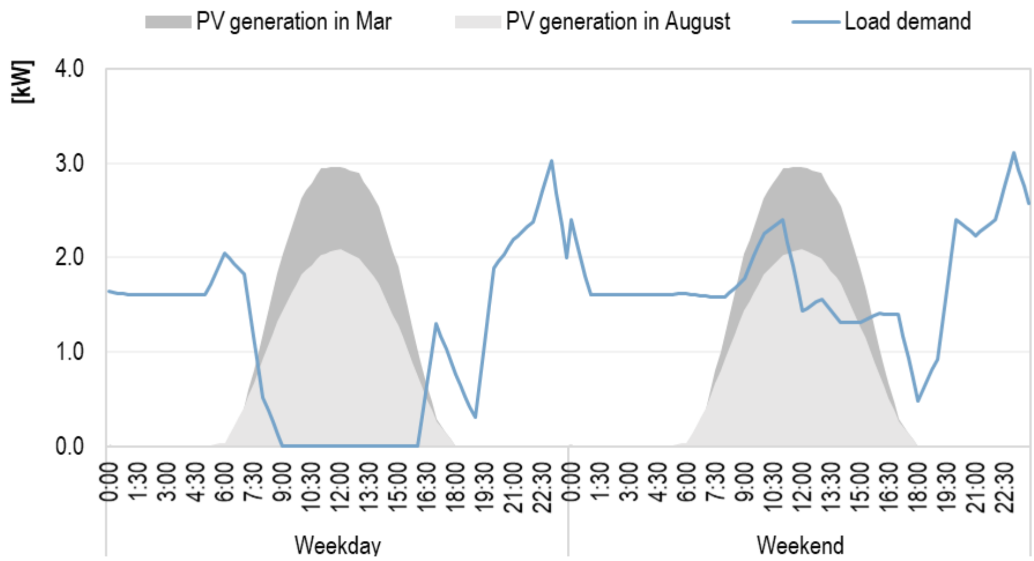


Figure 5.10 Load demand and PV generation profile of reference building without energy storage

The average PV generation of the 5 kWp PV system is approximately 1,261 kWh/kWp, where the highest PV generation occurs in March and the lowest PV generation is in August due to the rainy season (Figure 5.11).

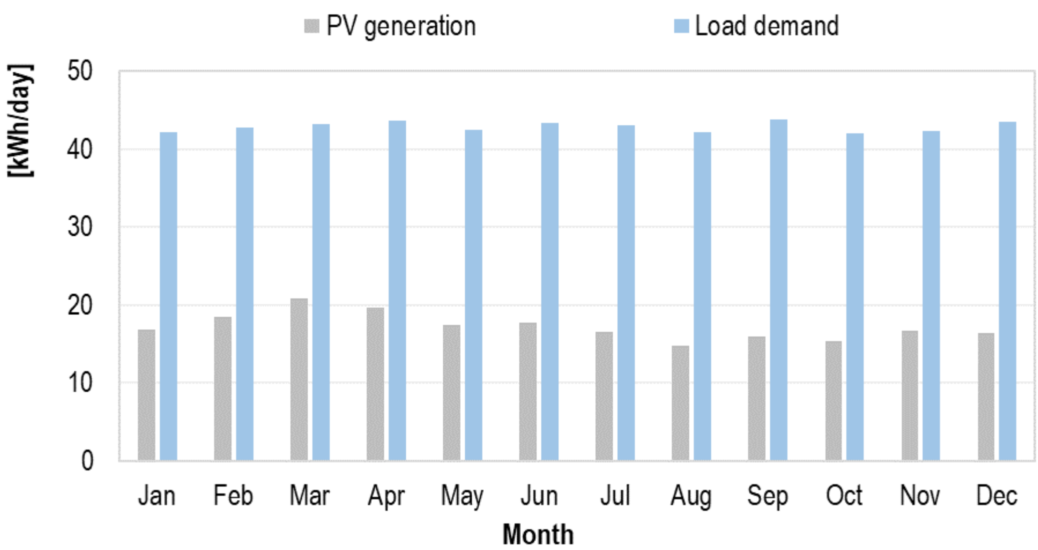


Figure 5.11 Average load demand and 5 kWp PV generation

The rated load in the new network is assumed at 7 kW, 0.85 lagging, while the existing buildings are varied between 1-7 kW randomly. The main load demand is from the cooling energy for the residential building. This research focuses on the extreme cases for the highest and the lowest PV generation in Mar and August, respectively, to examine the power quality impacts.

5.5 PV capacity sensitivity cases

The PV capacity sensitivity analysis can help to address the maximum PV hosting capacity in the LV network. The research investigates the PV penetration rate sensitivity at 0%, 15%, 50%, and 100%. Due to the difference in transformer capacity and household numbers in existing and new networks, the PV capacity per household is defined differently. This research examines the PV topology in two cases: 1) equally distributed to investigate the extreme case (Table 5.7) and 2) end of the feeder to examine the weakest topology with PV (Table 5.8).

Table 5.7 PV penetration rate sensitivity cases of existing network

Penetration rate	**Total PV capacity**	**Distributed PV case**		**End of the feeder case**	
		Number of houses with PV	**PV capacity per household**	**Number of houses with PV**	**PV capacity per household**
0% penetration	0 kWp	48	0 kWp	0	0 kWp
15% penetration	38 kWp	48	0.8 kWp	8	5 kWp
50% penetration	125 kWp	48	2.6 kWp	25	5 kWp
75% penetration	188 kWp	48	3.9 kWp	25	7.5 kWp
100% penetration	240 kWp	48	5.2 kWp	25	10 kWp

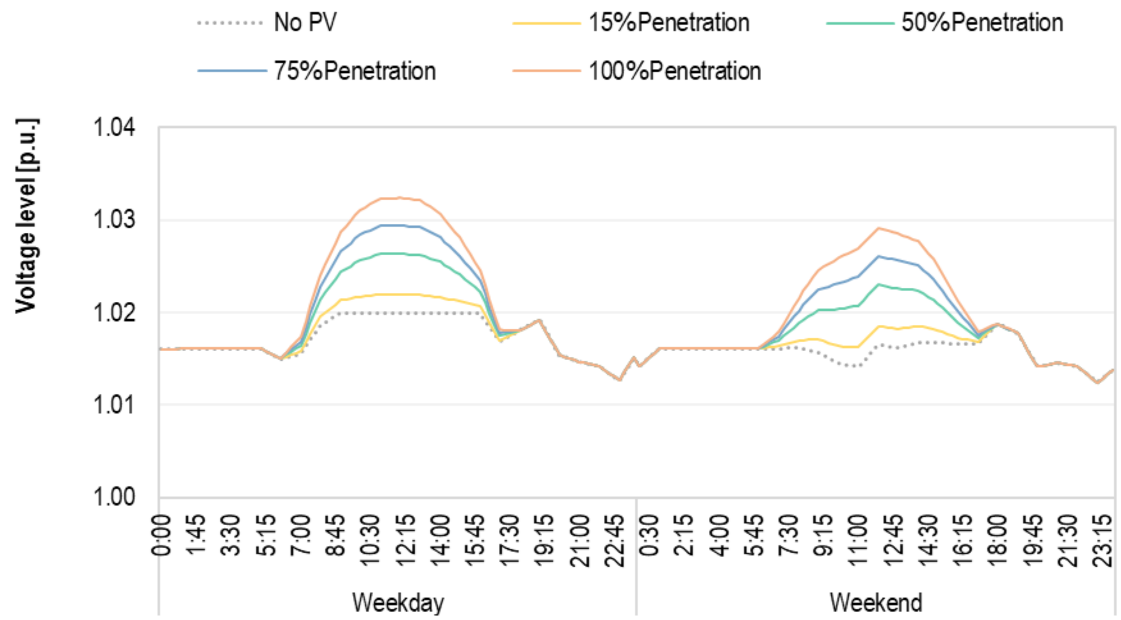
Table 5.8 PV penetration rate sensitivity cases of new network

Penetration rate	**Total PV capacity**	**Distributed PV case**		**End of the feeder case**	
		Number of houses with PV	**PV capacity per household**	**Number of houses with PV**	**PV capacity per household**
0% penetration	0 kWp	36	0 kWp	0	0 kWp
15% penetration	60 kWp	36	1.6 kWp	12	5 kWp
50% penetration	200 kWp	36	5.5 kWp	26	7.5 kWp
75% penetration	300 kWp	36	8.3 kWp	30	10 kWp
100% penetration	400 kWp	36	11.1 kWp	26	15 kWp

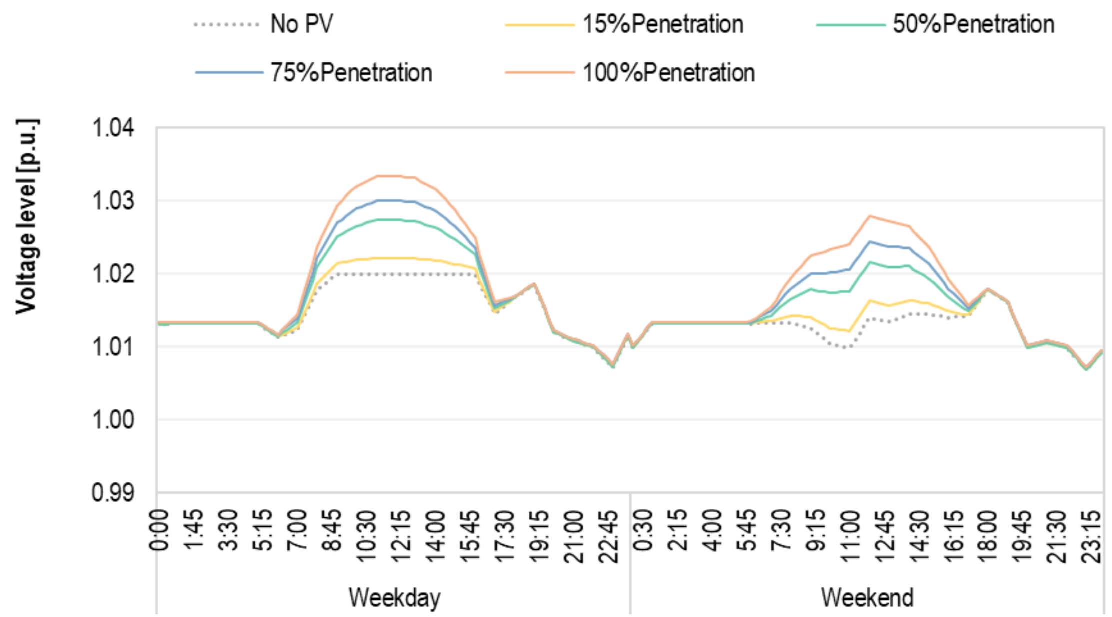
5.6 Investigation on voltage rise

5.6.1 Distributed PV case

Voltage rise is a crucial power quality issue under high PV integration in a low voltage network. The results show that the PV penetration rate is limited to 75% of their transformer's capacity for both existing and new networks (Figure 5.12).



(a) Existing network

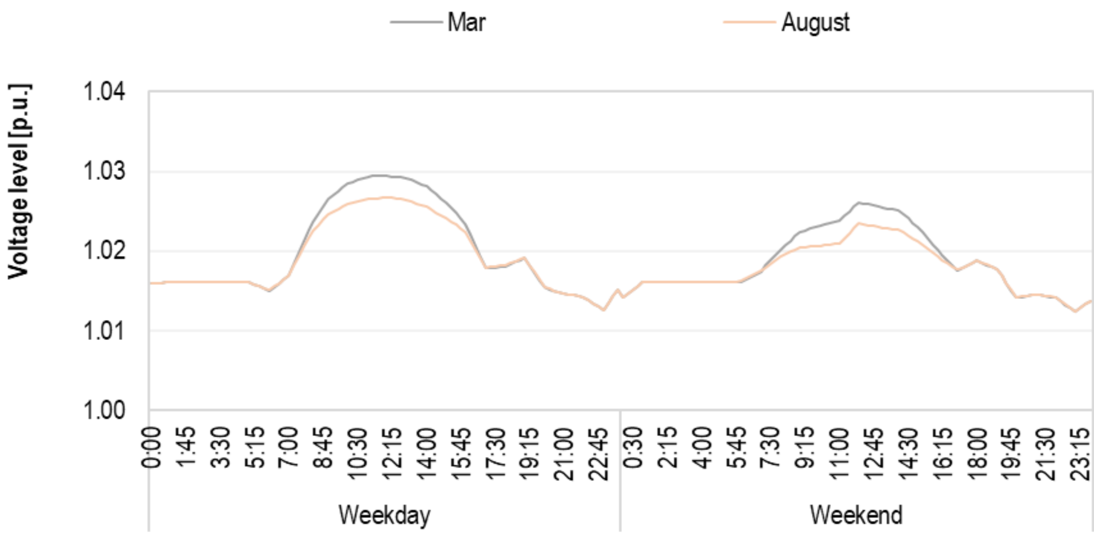


(b) New network

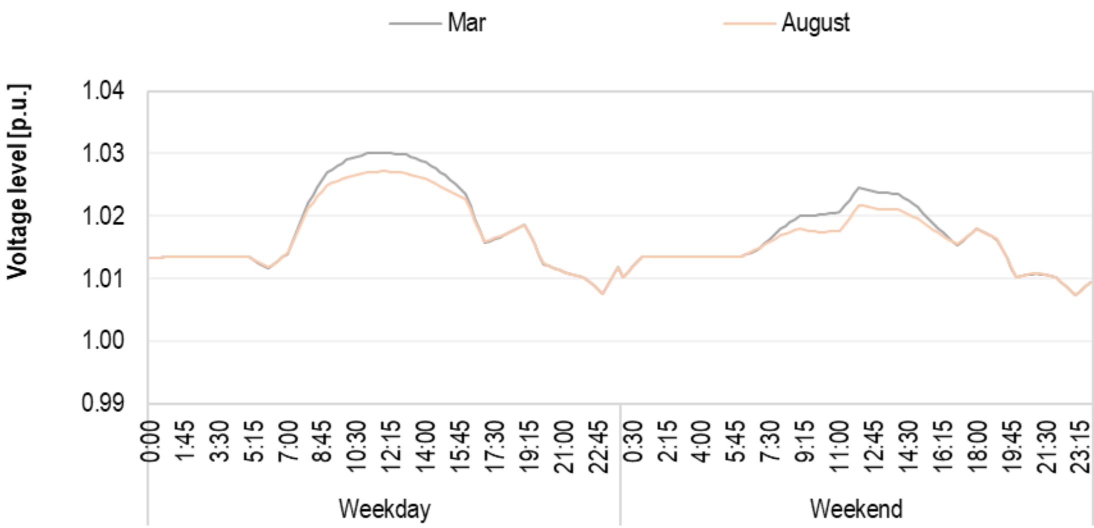
Figure 5.12 Voltage level at different PV penetration levels in March of the distributed PV case in existing and new networks

The voltage problem is worse on the weekday than on the weekend due to the light load during the daytime when the PV system generates energy. The 100% PV penetration results in an overvoltage problem for both the existing and new networks. At 15% of PV penetration rate, the voltage rise is approximately 1.02 p.u., which is higher than the non-PV case of 0.02%. It can be clearly seen that the total PV capacity can be increased to be over 15% but limited to 75% of the distribution transformer.

In addition, the solar irradiation has a direct influence on the voltage rise in the LV network during the light load period where there is a mismatch between energy demand and supply. The voltage level from high PV integration in March is higher than in August due to the high solar irradiation (Figure 5.13).



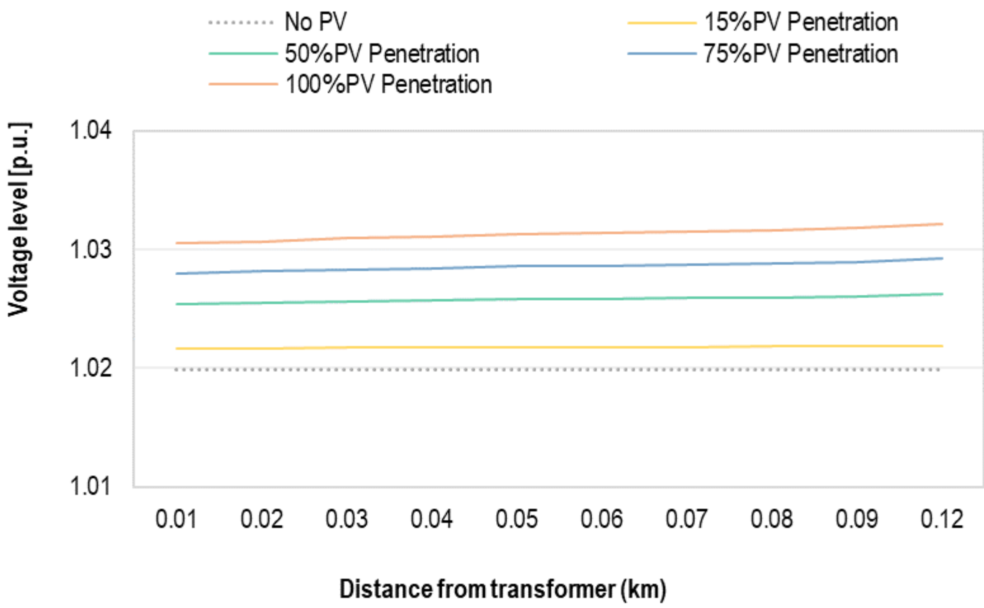
(a) Existing network



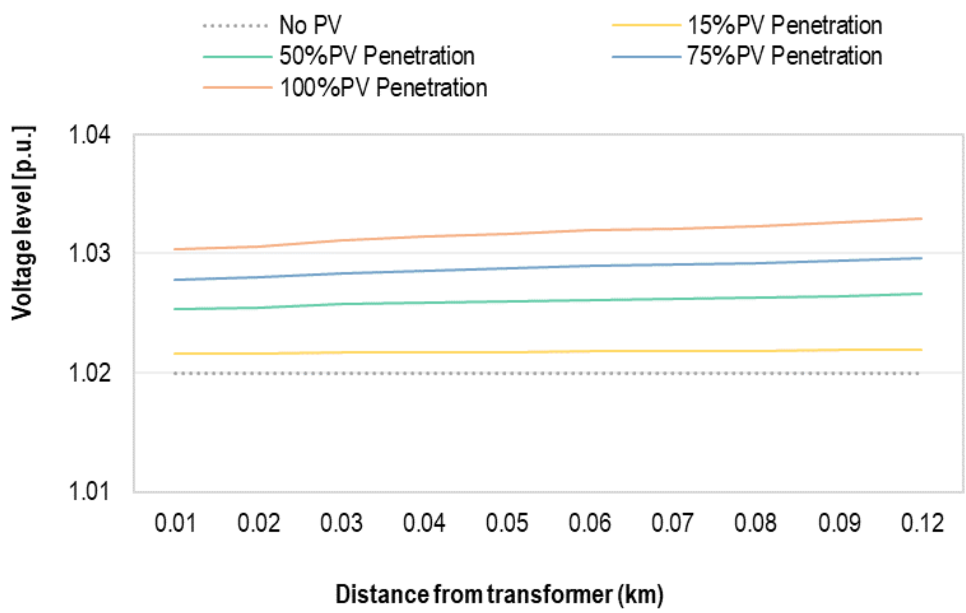
(b) New network

Figure 5.13 Voltage level at 75% PV penetration at the farthest bus of the distributed PV case in existing and new networks

The distribution system operator (DSO) should be alert during the light load period (weekday) in the summer season for some LV networks with high PV integration. Generally, the voltage drops along the feeder without the PV system and it increases when integrated into the PV system in the LV network at the end of the feeder. The farthest bus has a higher voltage level than the nearest bus due to the line impedance, which is the weakest location for integrating PV under light load conditions (Figure 5.14).



(a) Existing network



(b) New Network

Figure 5.14 Bus voltage variation at different distances from the transformer in Mar at 13:00 PM during the weekday in existing and new networks

In the rural area where the feeder is longer than the urban area, the voltage level decreases along the feeder. Assuming the existing network in the rural area has a longer feeder than the urban area of 0.5 km, the voltage level then exceeds 1.03 p.u. at 75% PV penetration rate (Figure 5.15). In Germany, the distribution system operator pays close attention to rural areas where voltage control regulation is dependent on the situation. Topology planning with the appropriate active control measure must be taken into consideration for PV integration in rural areas.

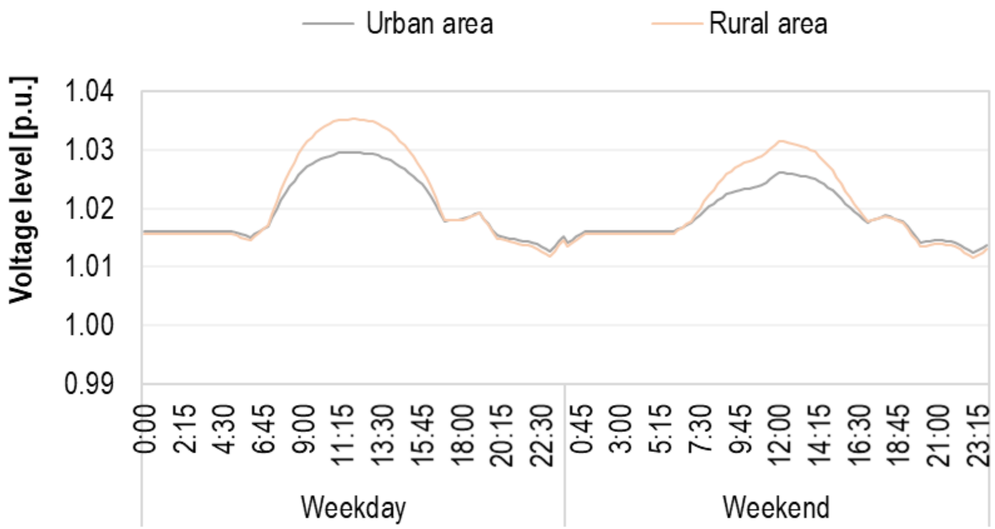
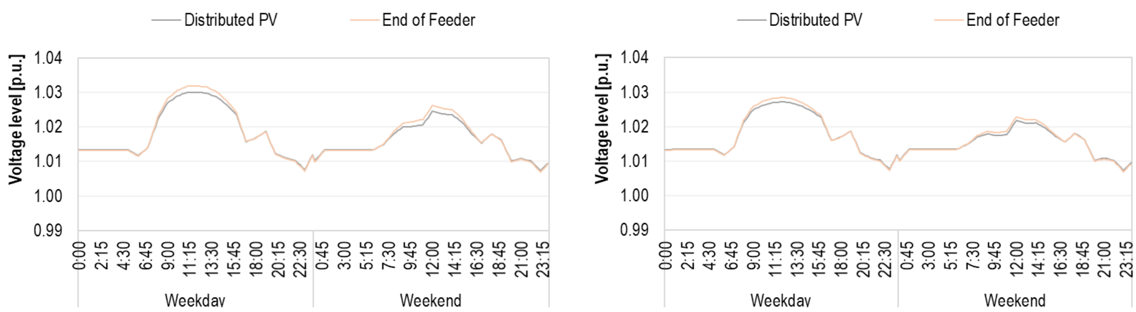


Figure 5.15 Voltage level at the farthest bus under 75% PV penetration in existing networks in urban and rural locations

5.6.2 End of the feeder case

Normally, the overvoltage occurs at the end of the feeder when the PV system is connected. This research emphasizes the extreme case of if all PV systems are connected at the end of the feeder. It can be seen that the voltage rise problem of the end-of-feeder case is more serious than the equally-distributed PV case because of the higher system impedance and the reversed power flow (Figure 5.16). The distribution system operator should pay careful attention to the farthest bus where the 75% PV penetration rate is connected to the LV network during high solar irradiation in March, which may lead to the voltage rise exceeding the standard limit.



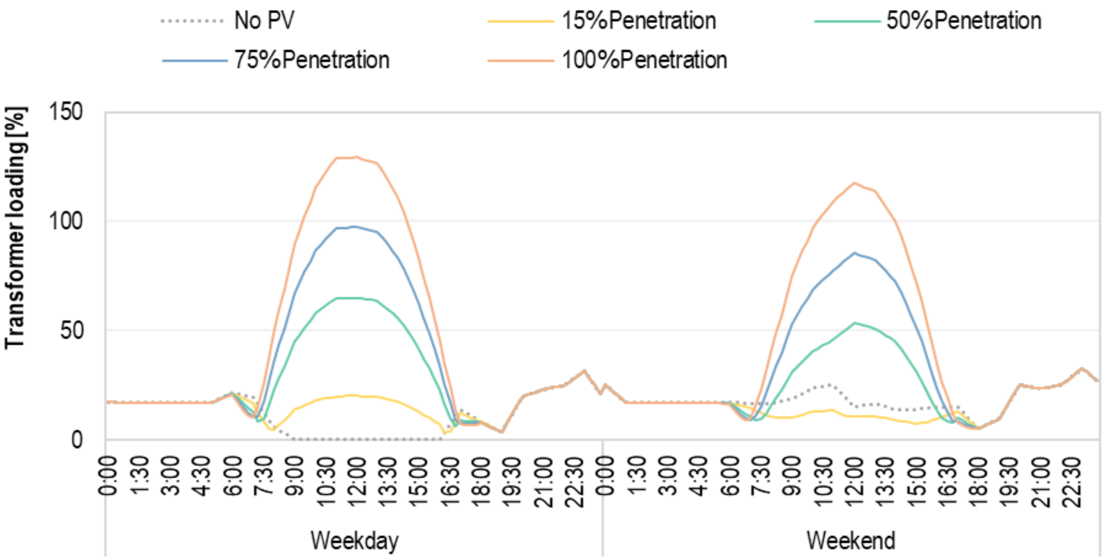
(a) March (b) August

Figure 5.16 Voltage level comparison between distributed PV and end of feeder cases at the farthest bus of 75% PV penetration in existing networks throughout Mar and August

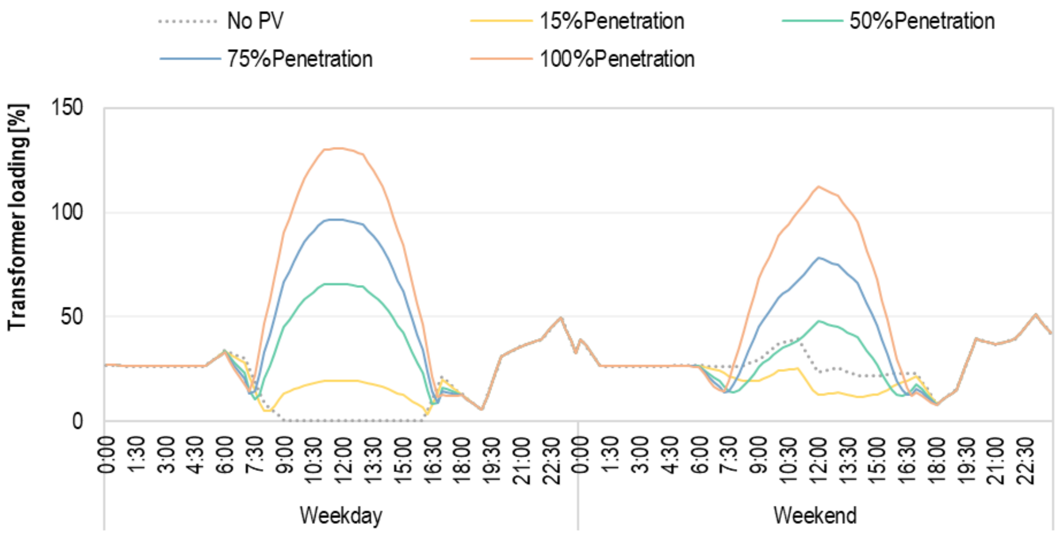
5.7 Investigation on transformer loading

5.7.1 Distributed PV case

At the normal condition without PV integration, the minimum transformer loading is approximately 0.5% (at 13:00 PM weekday) during the light load period and the maximum transformer loading is approximately 32% at 22:00 PM at night because of the cooling energy demand in the building. The 15% PV penetration increases the transformer loading by up to 20% during the daytime in a weekday (Figure 5.17).



(a) Existing network

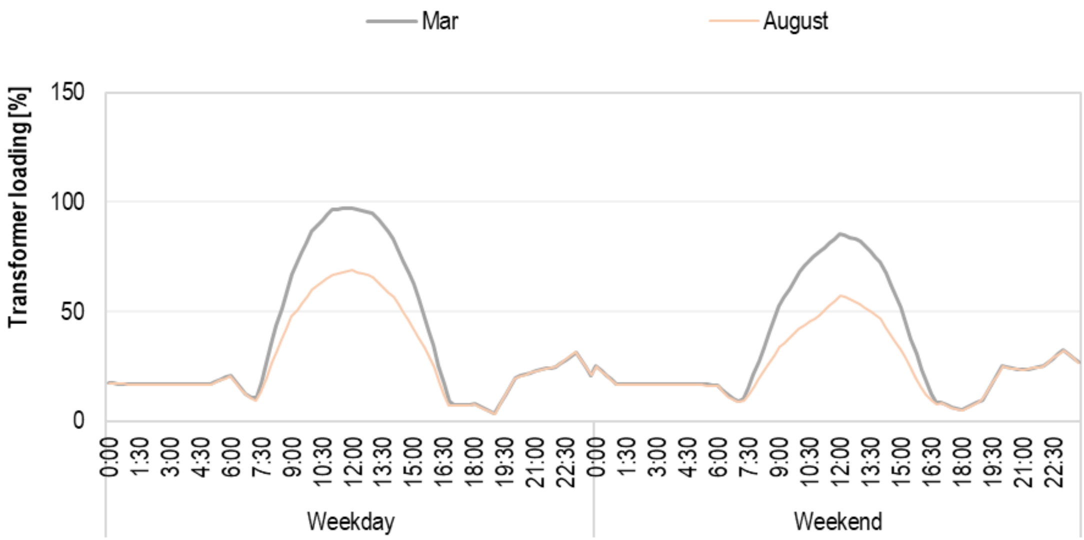


(b) New Network

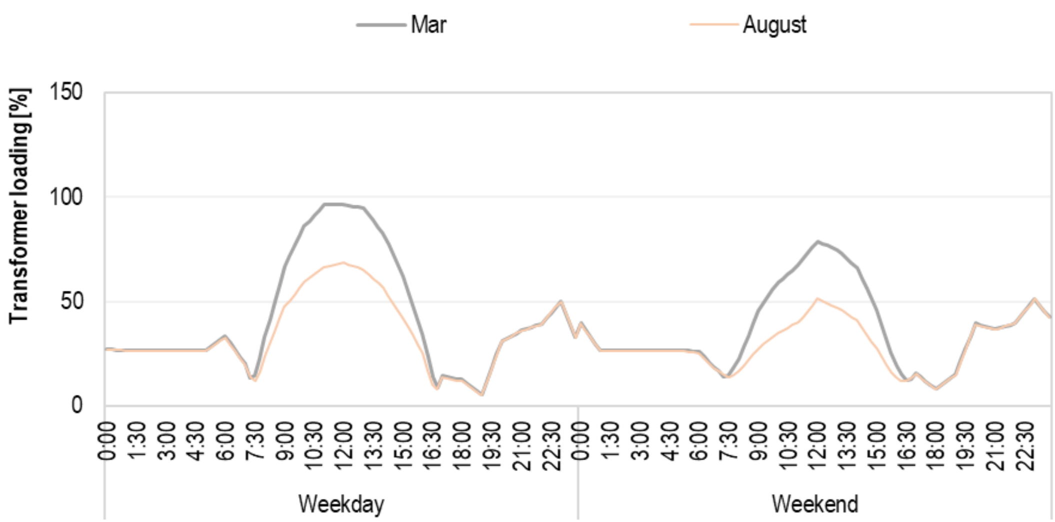
Figure 5.17 Transformer loading at different PV penetration levels of distributed PV case in existing and new networks in March

The overloading of the distribution transformer limits the PV penetration rate to 75%. Transformer overloading occurs when integrating 100% PV penetration. The on-load tap changer transformer might be the passive solution to lessen the transformer loading but it should be monitored and adjusted in advance.

Comparing between weekdays and weekends at the same time, the weekend has lower transformer loading due to the PV generation overlapping with the energy demand of the building. The transformer loading in August is lower than March due to the low solar irradiation, which results in low reversed power flow (Figure 5.18). The PV penetration rate is limited to 75% to keep the transformer loading from exceeding the limit and to prolong the transformer's lifetime.



(a) Existing network

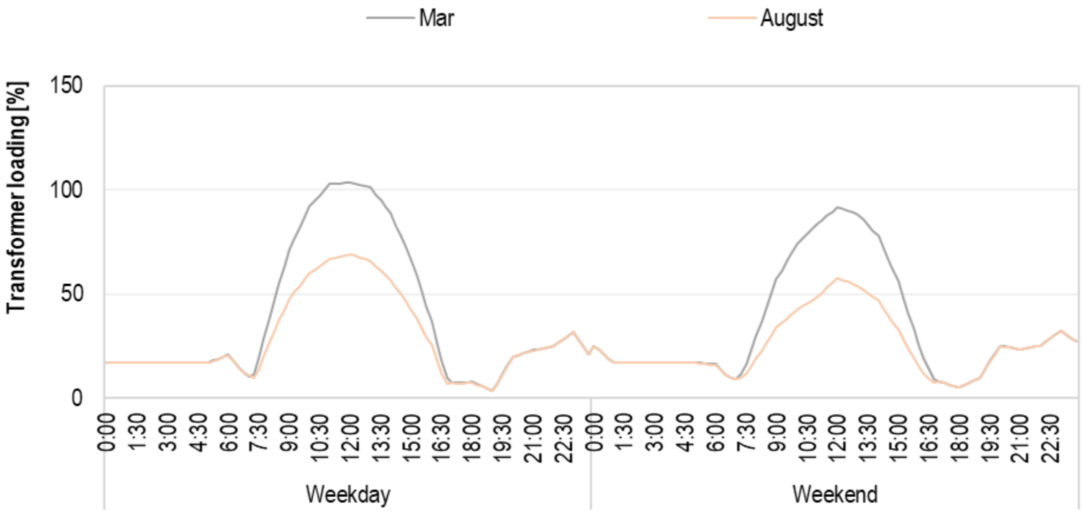


(b) New Network

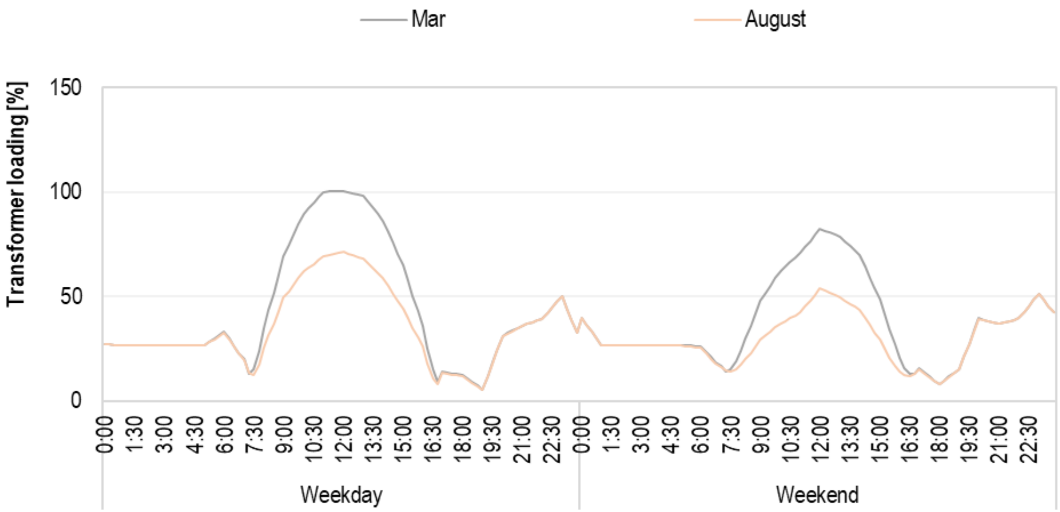
Figure 5.18 Transformer loading at 75% PV penetration of distributed PV case in existing and new networks in March and August

5.7.2 End of the feeder case

When integrating PV systems at the end of the feeder, it is found that the transformer is overloaded at 75% PV penetration rate (Figure 5.19). The transformer overloading occurs before the overvoltage issue. The transformer must absorb the feed-in power from a long distance, which then causes higher transformer loading. For the new network, the transformer loading is less than the existing network due to the stronger line and transformer which can absorb higher reversed power flow. The PV topology at the end-of-feeder case is crucial for the transformer loading and influential to its lifetime.



(a) Existing network

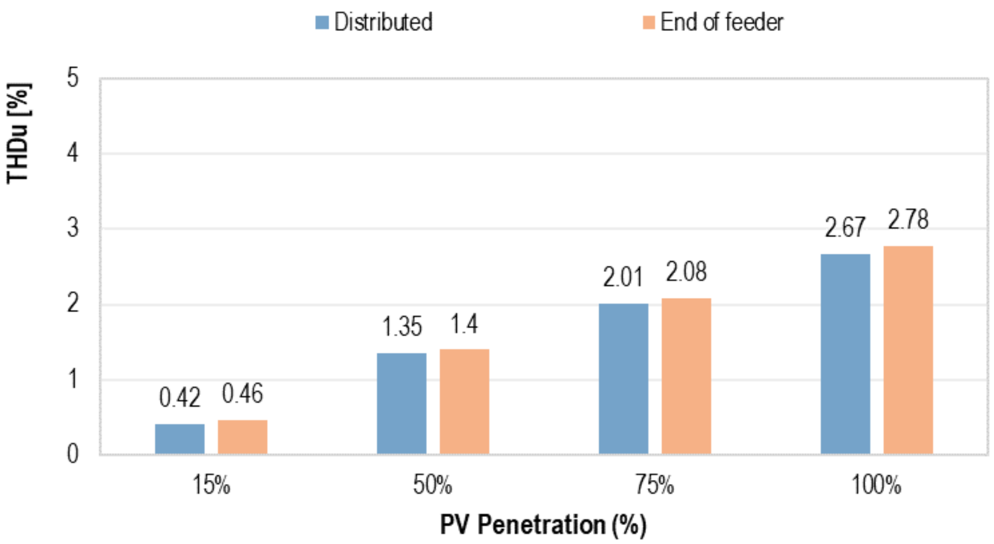


(b) New network

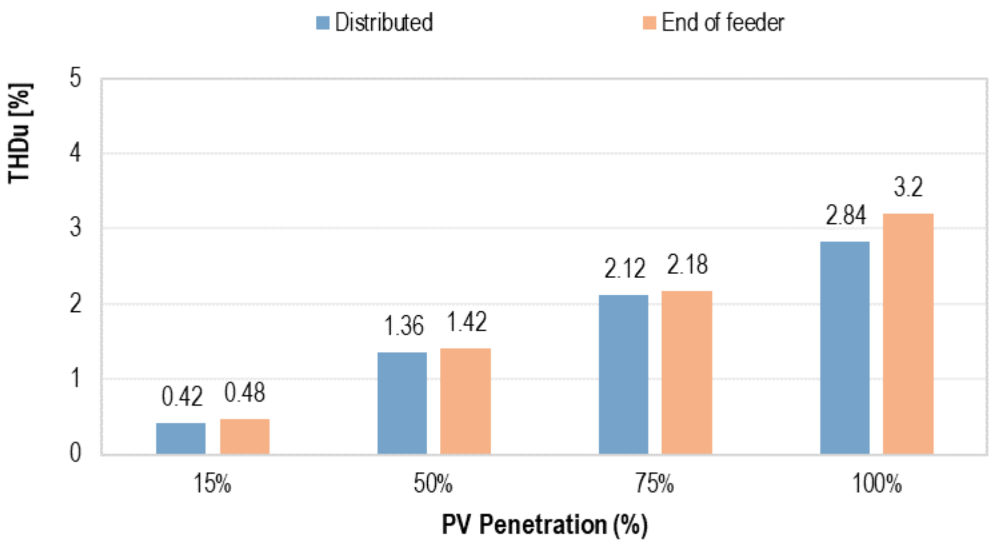
Figure 5.19 Transformer loading at 75% PV penetration rate comparison between distributed PV and end-of-feeder case in the new network in March and August

5.8 Investigation on total harmonic distortion (THD_U)

High PV penetration may generate the high harmonics in a low voltagea network. The results show that the THD_U increases slightly when there is higher PV capacity in the network. At zero PV penetration, the THD_U at LV bus is approximately 0.42% while the 75% of PV penetration results in a THD_U of 2%, which does not exceed the maximum standard limit of 5% (Figure 5.20). The PV penetration rate does not affect the THD_U significantly because the harmonics emission of the PV inverter is limited by the grid code and the manufacturer. It can be seen that the THD_U under the end-of-feeder case is higher than the distributed PV case. The THD_U is directly correlated with PV capacity and the distance where the PV located.



(a) Existing network



(b) New network

Figure 5.20 THD_U variation comparison between distributed PV and end of feeder cases in existing and new networks

This research has limitations with the real harmonic data from the PV system in the residential sector. It should be noted that the PV penetration rate is still low in the residential sector of Thailand. The harmonics from the PV inverter are assumed under the standard limit. There are several factors that can influence the total harmonics distortion in the system, e.g. control method of the inverter and background harmonics of the distributed network. The real data of the background harmonics requires extensive filed measurements. The electricity utility should be able to assess the harmonic and voltage distortion impacts based on the existing infrastructure for future system planning.

5.9 Voltage rise mitigation strategy

The voltage rise problem is quite critical when 75% PV penetration is considered in the LV network, which reaches the upper limit of the voltage level. The PV system topology at the end of feeder results in overvoltage at 75% PV penetration rate. Although the voltage level is permissible according to the grid code, it is worth investigating the voltage control approaches to reduce the voltage rise problem and increase the PV capacity in the LV system. According to the grid code of Metropolitan Electricity Authority, the total PV capacity is restricted by the distribution transformer capacity because of the safety presumption. In Germany, the prosumer must provide the reactive power by the operating power factor of the PV inverter, which is provided by the DSO, and the active power is limited up to 70% of its capacity. According to the Renewable Energy Sources Act (EEG) in Germany, the distribution system operator must implement the grid reinforcement to support PV integration where the power quality is crucial (GIZ, 2017; Stetz et al., 2013; EEG, 2012).

In Thailand's case, the "doing nothing" approach to neither the grid reinforcement nor the active voltage control measure is preventing the small prosumer in the LV network. Lessons learned from other countries, such as Germany, have proven to the DSO that prosumers can contribute to the power quality improvement solution. Nowadays, modern PV inverters can operate a flexible power factor to support the reactive power in the network. The energy storage system is utilized widespread for a centralized power quality control. The distributed energy storage system can also meet the technical requirements of the weak feeder. The PV inverter and energy storage can be the main contributors to improving power quality. This research intends to examine the following voltage control approaches, which can be applied in the context of Thailand in the future:

1. Grid reinforcement (GridRein)
2. Power factor characteristic (PFChar)
3. Voltage-dependent reactive power (Q(U))
4. Battery energy storage with reactive power support (BES with UQDroop)

The reference case of "doing nothing" is compared to the above alternative voltage control strategies to reduce the voltage rise problem of high PV penetration. This investigation only focuses on the existing network which - with the current electrical infrastructure - faces the possibility of high PV integration in the future.

5.9.1 Grid Reinforcement (GridRein)

Grid reinforcement is the simplest solution to handle high PV integration, e.g. replacing existing cables and transformers with larger ones, building a new distribution line, and so forth. Grid reinforcement is considered as a passive measure to deal with a future problem. Under the GridRein approach, the cable size and the transformer capacity are replaced with one of a bigger size in the existing network to foresee the possibility of the PV penetration being integrated into the LV system by over 75% (Table 5.9).

Table 5.9 Grid reinforcement in the existing network

Parameter/Case	Reference case	GridRein case
Transformer	250 kVA	400 kVA
Cable		
Pole to pole	50 mm^2	95 mm^2
Branch line	25 mm^2	35 mm^2

The result shows that by replacing the existing infrastructure with a bigger cable size and transformer capacity, it can reduce the voltage rise problem from 1.030 p.u to 1.025 p.u (Figure 5.21).

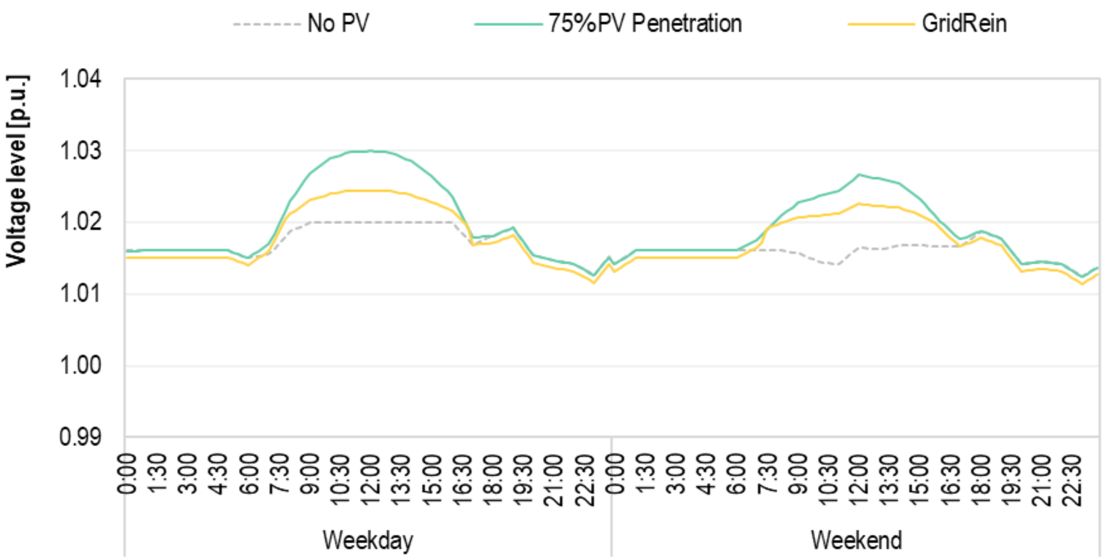


Figure 5.21 Voltage level in the existing network at the farthest bus in March by GridRein approach

Additional PV capacity can be integrated into the LV network after the grid reinforcement. The grid reinforcement can be implemented where more PV systems are likely to be integrated in the existing LV network without reactive power support from the prosumer. The grid reinforcement is a passive measure which requires a high investment in new infrastructure. Without grid reinforcement obligations, the DSO may take the economic element for improving the distribution network to prevent more PV systems in the LV network.

5.9.2 Power factor characteristic (PFChar)

In Germany, the prosumer is required to play an active role in feeding energy from the PV system with a capacity of less than 13.8 kVA to the LV network by operating the PV inverter at 0.95 lagging/leading. This research proposes a simple reactive power control in which the PV inverter is operated with power factor characteristics that are correlated with the rated active power.

The P_{limit} indicates the active power limit when the PV inverter starts absorbing reactive power and P_{max} refers to the maximum active power of the PV inverter. This research defines the P_{limit} at 70% of P_{max} for the operating power factor at 0.95 inductive operation (Figure 5.22). The annual energy loss of 3% is an acceptable value for PV capacity curtailment at 70% of its capacity (GIZ, 2017).

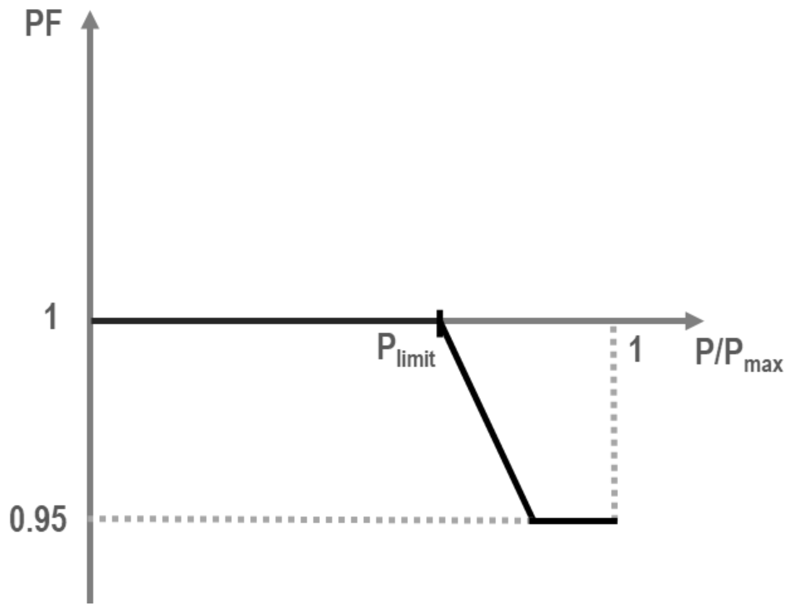


Figure 5.22 Power factor characteristic (PFChar) control strategy

The voltage level at 75% PV penetration rate decreases from 1.03 p.u. to 1.02 p.u. by operating the PV inverter at 0.95 power factor instead of the unity power factor (Figure 5.23). The PV inverter starts absorbing the reactive power when the active power from the PV system exceeds more than 70% of the rated value. The voltage level with the PFChar approach is close to the no PV integration level.

Currently, the PV penetration in Thailand is restricted by the DTR. The PFChar approach offers a high potential voltage control by allowing the PV owner to support the reactive power to the electricity grid network. This approach is very straightforward and can be applied in any location to mitigate the voltage rise problem.

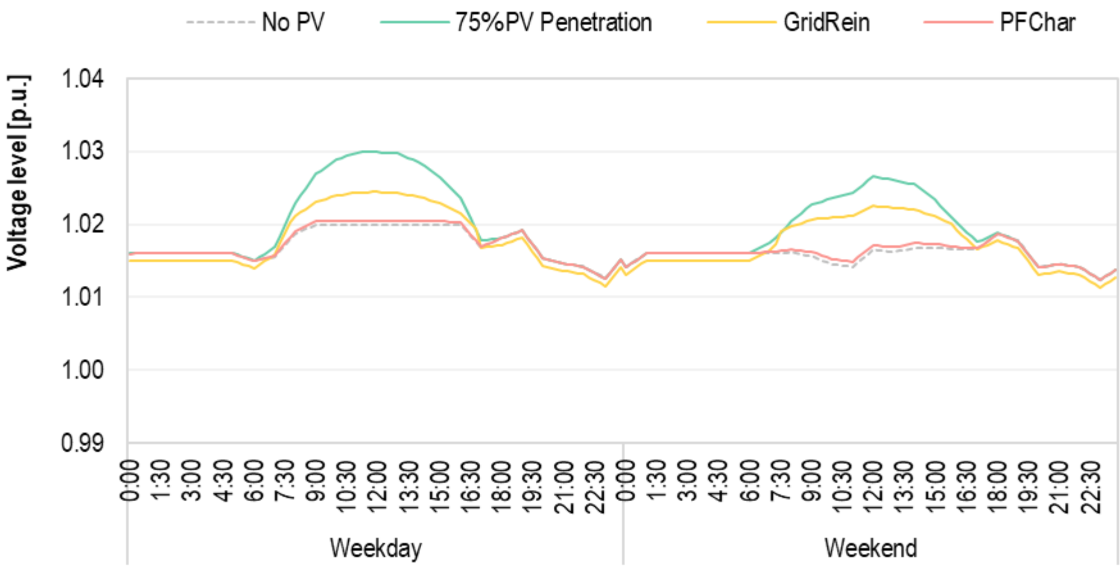


Figure 5.23 Voltage level at the farthest bus in the existing network in March by PFChar approach at 75% PV penetration rate

5.9.3 Voltage-dependent reactive power (Q(U))

The PFChar provides reactive power support by using the active power of the PV inverter as the controller. The voltage-dependent reactive power (Q(U)) offers adaptive reactive power control according to the voltage setpoint. The reactive power and voltage level are correlated by using a linear curve. The minimum and maximum voltage are set as the reference values, then the reactive power is adjusted according to the voltage range (Figure 5.24).

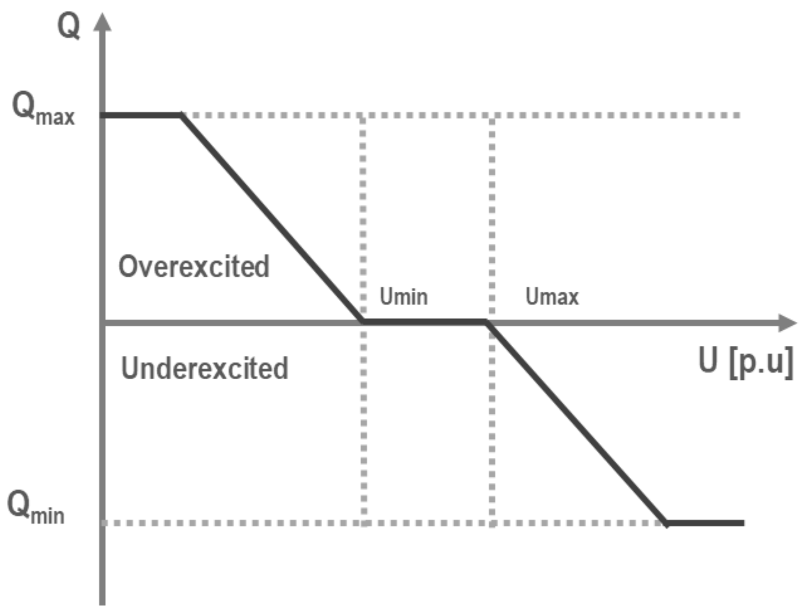


Figure 5.24 Voltage-dependent reactive power control Q(U)

If the voltage at the point of common coupling (PCC) is lower than the minimum set point, the PV inverter injects reactive power (overexcited operation) to increase the voltage level. On the other hand, if the voltage at the PCC is higher than the maximum setpoint, the PV inverter will absorb the reactive power (underexcited operation) to decrease the voltage level.

At 75% PV penetration rate, the peak voltage level increases from 1.02 p.u. to 1.03 p.u., compared to the no-PV case. The minimum and maximum setpoints are set to 1.01 and 1.02 p.u., respectively, to maintain the voltage level to be the same as the no-PV case.

The Q(U) approach gives the same voltage value compared with no PV integration case (Figure 5.25). Although the Q(U) and PFChar approaches give a similar voltage control result, the Q(U) approach offers a flexible reactive power support when it is not necessary within the voltage setpoint (U_{min} <U< U_{max}).

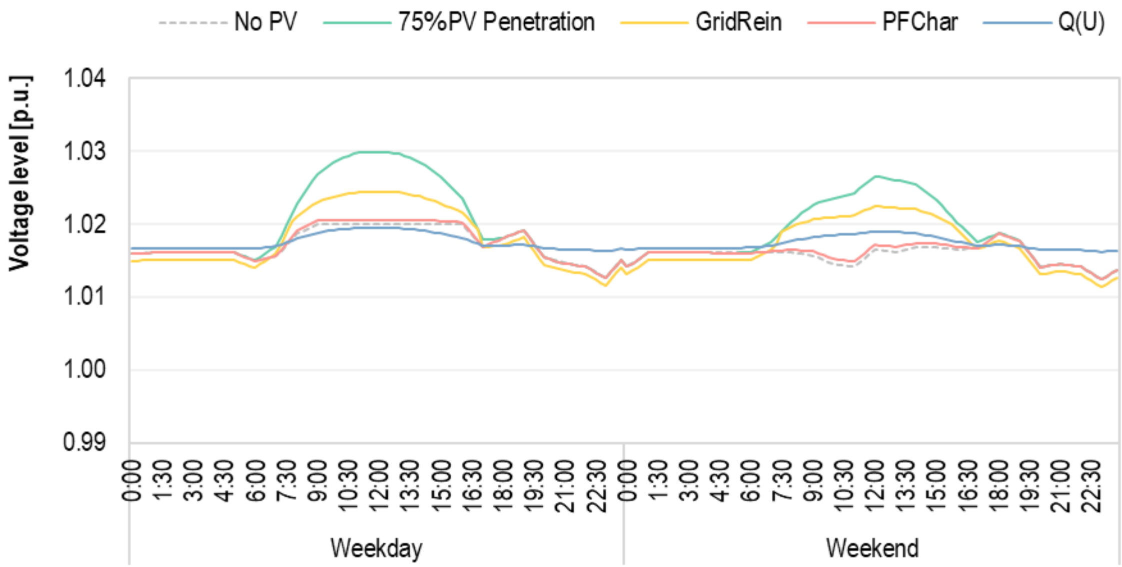


Figure 5.25 Voltage level at the farthest bus in the existing network in March by Q(U) approach at 75% PV penetration rate

However, the Q(U) approach has a weak reactive power contribution for the PV system at the nearest bus because it has a lower voltage level than the farthest bus. As a result, the farthest bus may experience a higher voltage from the reactive power support from the nearest bus. The Q(U) approach is commonly used in a rural area where the PV system is connected at the end of the feeder.

5.9.4 Battery energy storage with reactive power support (BES with UQdroop)

The above three measures can mitigate the voltage rise problem by operating the PV inverter. The voltage rise problem occurs during light load when integrated into the PV system in the LV network. The battery energy storage system can be utilized in several dimensions, such as increasing PV direct use and improving power quality. Without the voltage control measure, the energy storage system (ESS) can curtail the amount of reverse power to the grid and also increase the PV direct use at the same time. The integration of the battery energy storage system with the voltage control system can offer energy services to the DSO by providing reactive power support correlated with voltage level data.

This research proposes the integration of the distributed battery energy storage system and the voltage control strategy. In this context, the battery energy storage application is deployed to mitigate the voltage rise problem by using an adaptive reactive power control. The voltage reactive droop control (UQDroop) offers the advanced voltage control strategy by adjusting the amount of reactive power according to the voltage level data (Figure 5.26).

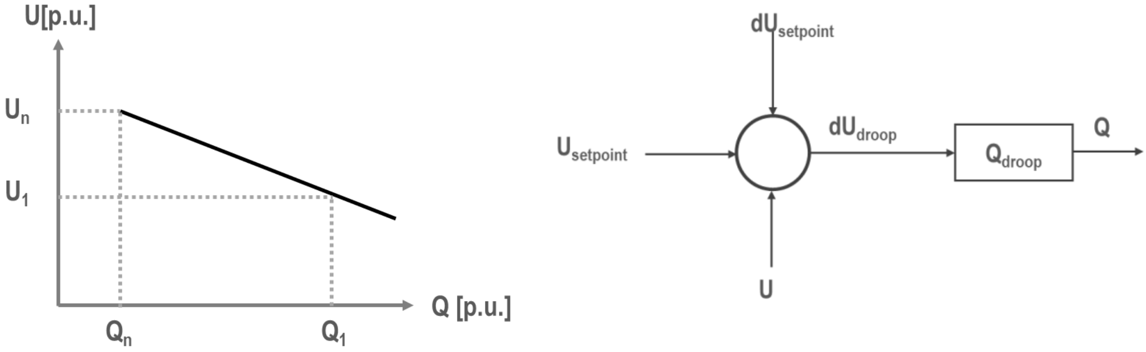


Figure 5.26 UQDroop control strategy

The algorithm of UQDroop control is straightforward by defining the droop value (d) and measuring the actual voltage (U_1) at the bus where the PV inverter is connected. The increasing voltage results in lower reactive power demand. In other words, reducing voltage results in additional reactive power contribution. The additional reactive power (Q_d) can be calculated from Eq. 5.6, Eq. 5.7, and Eq. 5.8 (DIgSILENT, 2017). The actual voltage is varied over time from the PV system and energy consumption in the building. Hence, the battery energy storage system with UQDroop offers a responsive voltage control strategy.

$$U_1 = U_n - \triangle U_d \qquad \text{(Eq. 5.6)}$$

$$\triangle U_d = \frac{Q_1 - Q_n}{Q_d} \qquad \text{(Eq. 5.7)}$$

$$Q_d = \frac{S_n \times 100}{d} \qquad \text{(Eq. 5.8)}$$

where:

U_n	: nominal setpoint voltage (p.u.)
U_1	: actual voltage (p.u.)
$\triangle U_d$	: the voltage deviation (p.u.)
d	: droop value specific
S_n	: the nominal apparent power
Q_n	: nominal setpoint reactive power (p.u.)
Q_1	: actual reactive (p.u.)
Q_d	: additional reactive power for 1% of voltage deviation

The droop value is presented as a percentage for the required additional reactive power compared to the nominal apparent power of the PV system. For example, the droop value of 1% and a voltage deviation of 0.01 p.u. requires the additional reactive power of 100% of the nominal apparent power of the PV system. In Germany, the voltage-reactive power characteristic is provided by the distribution system operator (DSO) (Pantziris, 2014).

Generally, the excess PV generation is fed back to the LV network which causes the voltage rise in the feeder. The battery energy storage stores excess energy which can reduce the voltage rise problem and then delivers the energy for the later use. It can be seen that only the battery energy storage system with a fixed power factor can reduce the voltage rise problem during the daytime when the PV system generates energy (Figure 5.27).

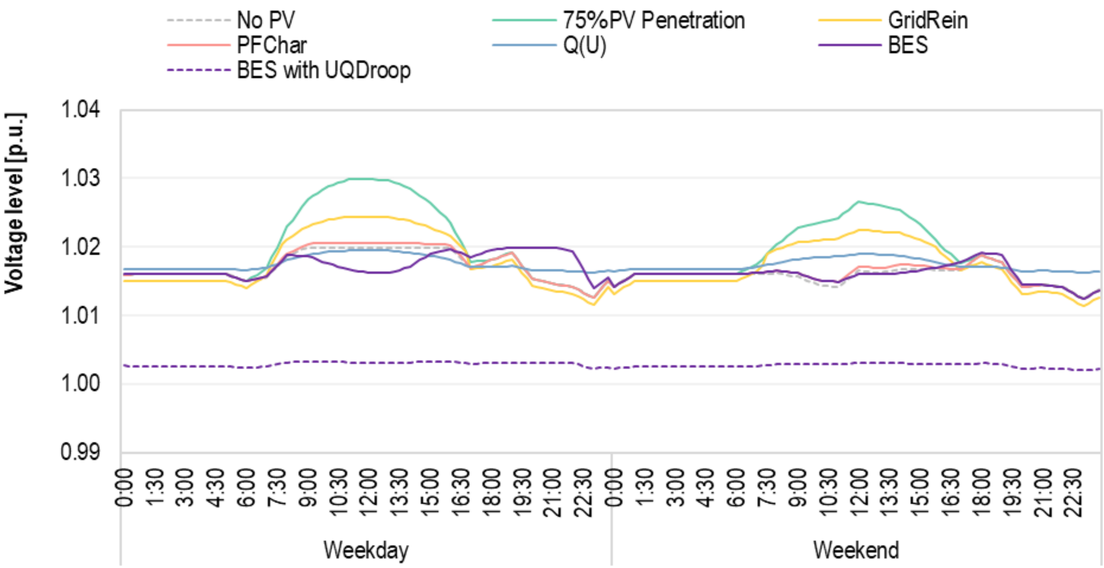


Figure 5.27 Comparison of voltage control strategies

The battery energy storage with the UQDroop approach can provide reactive power to the low voltage network in both daytime and nighttime. The decision making on the battery energy storage system utilization should be a trade-off between the PV direct use and ancillary service to the low voltage network - whether the profit of the additional investment in a larger battery energy storage system with the incentive for providing the energy service to the distribution system operator is greater than the direct use.

In addition, the UQDroop control highly requires real-time communication from the distribution system operator to monitor and provide the droop characteristic for voltage and reactive power control. The battery energy storage system can be deployed in centralized and decentralized approaches. The centralized battery energy storage system application can improve the overall voltage level by using the most critical feeder as the reference value, while the decentralized battery energy storage system utilization can lessen the voltage rise problem at the critical feeder.

5.10 Voltage control strategies comparison

The investigation has indicated that the existing network can support PV penetration up to 75% without grid reinforcement. Additional PV capacity can be combined with the proper voltage control strategies (Table 5.10). It was found that the battery energy storage system with the UQDroop control strategy offers the best voltage control of all time, followed by the Q(U), PFChar, and grid reinforcement, respectively.

Table 5.10 Voltage control strategy comparison

Strategy	Potential	Advantage	Recommendation
Grid reinforcement (GridRein)	Low	- Simple solution by the DSO	- High investment cost
Power factor characteristic (PFChar)	Medium	- Enhance high PV capacity in the system - Can be deployed in any location	- Proper grid code planning
Voltage-dependent reactive power (Q(U))	Medium	- Provide responsive voltage control - Best deployment at the farthest bus	- Proper grid code and topology planning
Battery energy storage with reactive power support (BES with UQdroop)	High	- Enhance PV direct use and voltage control	- Proper incentive support for battery energy storage system - Comprehensive monitoring and communication system

Grid reinforcement is the simplest solution from the DSO's point of view as it does not require an active role from the PV prosumer for the voltage control support. However, the investment cost in new infrastructure is crucial, which means the DSO can use it as the reason to prevent more PV systems in the LV network.

The PFChar method is the modest solution for both prosumers and the DSO by indicating the power factor of the PV inverter at the active power setpoint. The PFChar allows more PV systems into the LV network instead of investing in new infrastructure. The Q(U) approach has a similar voltage control contribution with the PFChar but the Q(U) can provide the adaptive reactive power control according to the voltage setpoint.

The battery energy storage (BES) with advance control strategy can be employed in both a decentralized and a centralized manner, but it requires proper incentive support to the BES system owner for providing the ancillary service to the grid network. The centralized BES option tends to improve the voltage level for the whole feeder, whereas the decentralized BES can be deployed in the high-risk bus with lower investment costs. The decentralized BES system is the more favorable approach as it can be implemented at the critical voltage rise problem. The network of distributed BES systems can perform as a virtual power plant for smoothing the power in the LV network rather than investing in new infrastructure.

5.11 Conclusion

High PV integration raises power quality concerns for the low voltage (LV) network. The conservative control approach of limiting the PV penetration rate at 15% of the distribution transformer (DTR) is considered as the main barrier for small renewable energy players in smart grid development. The results show that the farthest bus is the weakest location for high PV integration during light load compared to the nearest bus. If there is high PV generation, a higher voltage level occurs. The transformer loading of the high PV generation also increases, which can reduce its lifespan due to the higher loss. It was also found that total harmonic distortion at high PV penetration is acceptable due to the limitations of the current harmonics of the PV inverter, according to the grid code. Extensive measurement of the harmonics effect is required for the background harmonics for future system planning.

The maximum PV penetration of 100% cannot be deployed in the existing infrastructure as it causes overvoltage and a transformer overload problem. The PV hosting capacity in the existing network is limited to 75% of PV penetration, which keeps the voltage level in the permissible range. To allow more PV systems in the existing network, it requires either grid reinforcement by the distribution system operator or an active voltage control support from the PV prosumer. The grid reinforcement approach requires high investment costs of which the distribution system operator can use as a reason to prevent more PV systems in the LV network.

Operating the power factor of PV inverters is the reasonable approach from the distribution system operator and prosumer’s point of view, as it allows the PV prosumer to provide the reactive power support. The PV inverter with power factor control is currently available on the market. However, the PV owner must invest in a larger PV inverter system to maximize the PV output while providing the reactive power for the LV network. The PFChar option can be implemented in any location of the feeder. The voltage-dependent reactive power or called Q(U) technique provides adaptive reactive power control, which is the main advantage for a PV system located at the end of a long feeder in a rural area.

Only the battery energy system (BES) can reduce the voltage level during the day, which is the same principle as active power curtailment. The BES has two-fold benefits of storing excess energy for individual use and providing energy services to the electricity grid network. The BES with advanced voltage reactive droop control (UQDroop) can mitigate the overall voltage rise problem by defining the preferred voltage profile as the controller. The PV owner should make the trade-off regarding the profit between PV direct use and providing energy services to the low voltage network where the incentive is essential.

Currently, the grid code in Thailand restricts the PV capacity by the distribution transformer due to the safety presumption of the distribution system operator. Active voltage control is the more favorable option, rather than grid reinforcement, as the active voltage control measure is only required at the critical feeder instead of at every location. Instead of investing in new infrastructure to handle more PV systems in the low voltage network, the distribution system operator can offer an active role to PV prosumers. A strong focus on energy policies in the grid code revision is essential for the residential sector to participate in clean energy development in Thailand.

Chapter 6

Economic Assessment

6.1 Introduction

The technology assessment has proven that the integrated technology package of the energy efficiency measures (EEM), PV system, and ice thermal energy storage system are the most favorable options for energy performance. However, the consumer often considers the purchase cost rather than the life cycle cost in the decision-making process. The energy cost is not included in the purchase cost; hence the consumer must accept the high energy expenses from poor building energy design later.

This chapter presents the economic analysis based on the life-cycle cost principle for a detached residential building with integrated technology options. The environmental impact from the building operation is also considered as the carbon dioxide emissions cost. The willingness to pay (WTP) of integrated technology options in residential building is investigated within the Thai consumer context. The key findings of the economic analysis results shall encourage the consumer's future purchase decision, the policymakers for future energy policy design, and relevant incentive support for high potential technology options in residential building.

6.2 Economic analysis framework

The economic analysis framework is based on the global cost evaluation, according to the EN 15459 standard (Figure 6.1) (EC, 2012). The global costs consist of the initial investment cost, replacement cost, energy cost, and maintenance cost. The benefits include energy saving, incentives, and residual value at the end of the life cycle. All cost parameters are based on the net present value method by using a discount rate. The power development plan (as mentioned in Chapter 2) is considered for the levelized cost of electricity (LCOE) and carbon dioxide emissions by using Long-Range Energy Alternatives Planning System (LEAP) software. The LEAP software is developed by the Stockholm Environment Institute (SEI) and is widely used for long-term energy generation system planning and climate change assessment (Heaps, 2016).

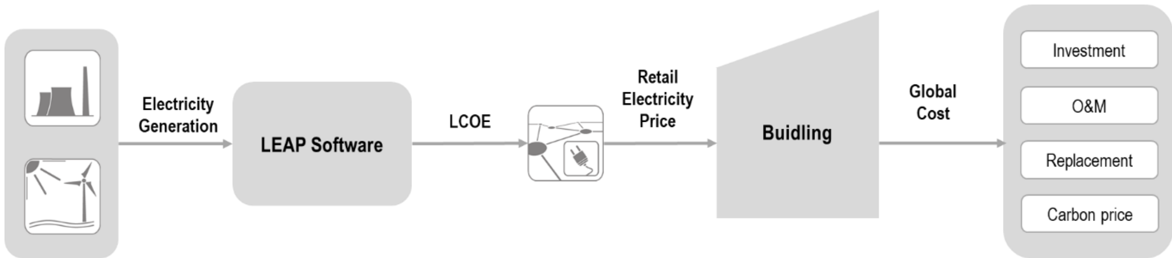


Figure 6.1 Economic assessment framework

Thailand does not have the emissions trading system (ETS), therefore the carbon dioxide price is not yet available in Thailand. For the simple assessment on environmental impact, this research uses the minimum carbon dioxide price which is indicated in EN 15459 standard.

6.3 Levelized cost of electricity generation (LCOE) in Thailand

6.3.1 Cost parameter assumption

The levelized cost of electricity (LCOE) represents the unit generation cost of electricity, which covers the total investment cost and electricity generation over the project's lifetime and is based on the net present value method (Eq. 6.1) (NREL, 2011). The LCOE can be compared with different power plant technologies, e.g. the combined cycle, thermal power plant, and renewable energy. The list and share of power plants for the Thai electricity system follows the power development plan 2015. The Thai electricity generation system still relies on fossil fuel, mainly from natural gas.

$$\mathrm{LCOE} = \frac{I_o + \Sigma_{t=1}^{n} \frac{A_t}{(1+r)^t}}{\Sigma_{t=1}^{n} \frac{M_{t,el}}{(1+r)^t}} \qquad \text{(Eq. 6.1)}$$

where

I_o	: investment expenditures (EUR)
A_t	: annual total cost (fuels, O&M costs) in year t (EUR)
$M_{t,el}$	: electricity generation in year t (kWh)
r	: real discount rate (%)
n	: economic operation lifetime (years)
t	: year of lifetime (1, 2, …n)

However, the PDP 2015 only projected the power plant plan until the year 2036, but this study analyzes it until the year 2066 50-year building lifetime. The share of power plants from 2036 onwards is assumed to be the same as the year 2036. The electricity demand from the year 2037 to the year 2066 increases by 3% per annum, which is the average growth rate of electricity demand from the years 2016 to 2036.

The future primary energy price is referenced from the study by the IEA (IEA, 2017b) as shown in Table 6.1. The assumption of capital cost, fixed operation and maintenance (O&M), and variable O&M (included fuel cost) are retrieved mainly from EIA, EGAT and IRENA (Table 6.2) (EIA, 2018; Kamsamrong & Sorapipatana, 2014; IRENA, 2016).

Table 6.1 Fossil fuel price projection (IEA, 2017b)

Fuel/Year	Unit	2015	2020	2030	2040	2050	2060
Crude oil	EUR/bbl	59	92	129	144	159	172
Coal	EUR/tonne	74	84	97	101	105	107
Gas	EUR/MMBtu	11	11	14	14	15	15

Table 6.2 Assumption for the LCOE calculation by power plant type
(EIA, 2018; Kamsamrong & Sorapipatana, 2014; IRENA, 2016)

Type of power plant	Fuel	Capital cost (EUR/kW)	Fixed O&M (EUR/kW)	Variable O&M (EUR/MWh)	Lifetime (Years)
Thermal	Coal bituminous	550	35	26	40
	Coal lignite	1,000	35	10	40
	Fuel oil	600	35	20	30
	Diesel	600	35	30	30
	Nuclear	3,000	97	10	60
Combined Cycle Gas Turbine	Natural gas	550	19	26	30
Large scale PV	Solar	700	18	-	20
Rooftop PV		900	18	-	20
Wind	Wind	1,000	25	-	20
MSW	Waste	3,200	60	10	30
Biogas	Biogas	3,000	60	10	30
Biomass	Biomass	2,000	60	10	30
Small Hydro	Hydro	1,800	36	-	30
Large Hydro		2,000	36	-	60
Power purchase	Electricity	1,800	36	-	30

6.3.2 Discount rate assumption

The baseline discount rate is approximately 0.54% per annum according to Bank of Thailand (BOT), which reflects the real interest rate (1.5%) and the inflation rate (0.95%) (BOT, 2018). The real discount rate can be calculated from Eq. 6.2 and 6.3.

$$R_d(p) = \left(\frac{1}{1+r/100}\right)^p \qquad \text{(Eq. 6.2)}$$

$$r = \left(\frac{1+k}{1+i}\right) - 1 \qquad \text{(Eq. 6.3)}$$

where:

R_d : discount factor for the year i based on the discount rate r
p : number of the year from the starting period
r : real discount rate
i : inflation rate
k : real interest rate

The real interest rate reflects the return of the treasury bill, which is the risk-free rate. The discount rate is used to calculate the future value to the present value in the cash flow analysis in order to assess the risk of the investment and expected rate of return.

The general discount rate in the energy system analysis is between 3-6% for the household scale (BPIE, 2015; EC, 2012; Witt et al., 2015). The sensitivity analysis is useful because the discount rate influences the NPV for the private investor’s perspective. This research uses the discount rates of 1% and 3% for the sensitivity analysis, which have been used in several financial assessments in energy research contexts (Biebaut, 2017; BPIE, 2013; BPIE, 2015; Becchio et al., 2015; Kurnitski, 2011).

6.3.3 Assessment of levelized cost of electricity (LCOE) for Thai electricity system

By using the parameters in Section 6.3.1, the LCOE by technology is shown in Figure 6.2 where the blue dot represents the average value. The large scale of solar energy has an average LCOE of 4.7 cents EUR/kWh while small scale of solar rooftop has an average LCOE of 7.5 cents EUR/kWh, or higher than the large scale by approximately 37%. The minimum LCOE of the small PV system (PV rooftop) is approximately 4.7 cent EUR/kWh, which is cheaper than the upper LCOE of the CCGT. The LCOE of renewable energy technology can compete with the fossil fuel power plant due to the rapid investment cost reduction from the PV module and wind turbine components.

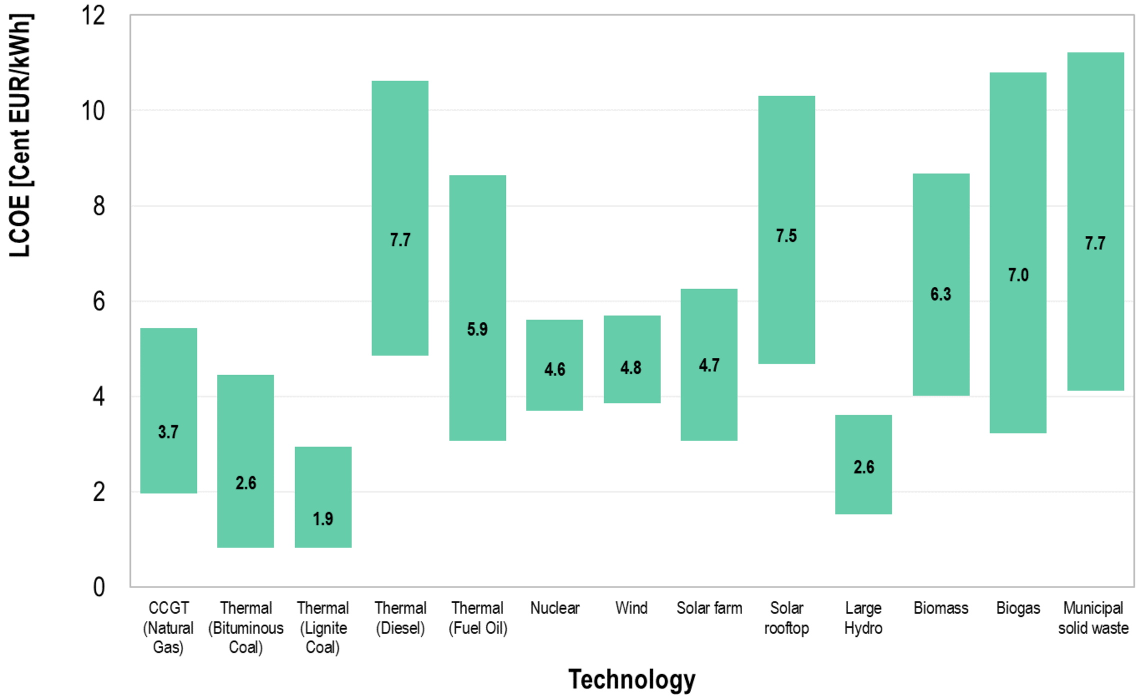


Figure 6.2 LCOE of Thai electricity system by power plant type

The coal-fired thermal power plant has the lowest LCOE of 1.9 cent EUR/kWh due to the low cost of capital investment and fuel price, while the diesel thermal power plant results in the highest LCOE of 7.7 cent EUR/kWh. The diesel and fuel oil thermal power plants are operated during the peak load only because of their high LCOE price.

This research excludes externality costs regarding environmental externalities and non-environmental externalities. The assessment of externality costs requires extensive background data for a specific country context. However, the carbon dioxide price is used for the environmental impact assessment in this research. The carbon dioxide price is shown in Section 6.5.4.

6.4 Thai retail electricity price

The retail electricity price in Thailand consists of generation cost, transmission system cost, distribution system cost, tax, fuel adjustment time (Ft) and the services fee (Figure 6.3). The generation cost is a major contributor of retail electricity price – making up 74% of the total. The distribution cost is approximately 0.01 EUR/kWh (EGAT, 2017b), while the transmission cost is around 0.004 EUR/kWh (EGAT, 2017b). This research projected the retail electricity price in Thailand by using the levelized cost of electricity (LCOE) data from Section 6.3 and taking the cost embodied in Figure 6.3 into account. The LCOE can be referred to the minimum electricity generation cost, which can break even over the project’s lifetime.

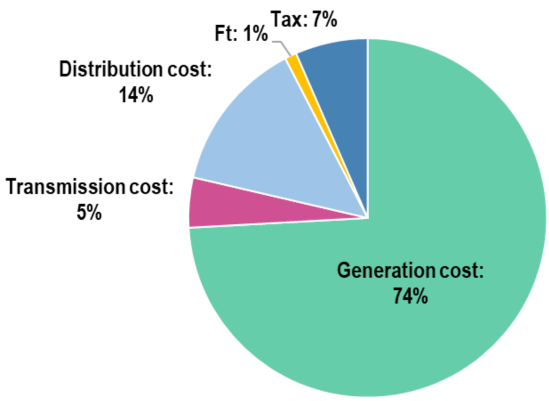


Figure 6.3 Retail electricity price embodied in Thailand (EGAT, 2017b)

The current retail electricity price in Thailand is approximately 0.1 EUR/kWh (EGAT, 2017b). The retail electricity price in Thailand is expected to increase due to the reliance on natural gas in power generation which must be imported from abroad, according to the power development plan (PDP) 2015 and the higher fossil fuel price projection. The retail electricity price in Thailand will reach 0.35 EUR/kWh in the next 50 years (Figure 6.4). It should be noted that the result of the retail electricity price in this study is based on the conservative transmission and distribution cost with the discount rate of 0.54%. The sensitivity analysis of the discount rate of 1% and 3% will be assessed for the global cost calculation analysis in Section 6.9. The retail electricity price projection will be used to calculate the global cost in Section 6.5.

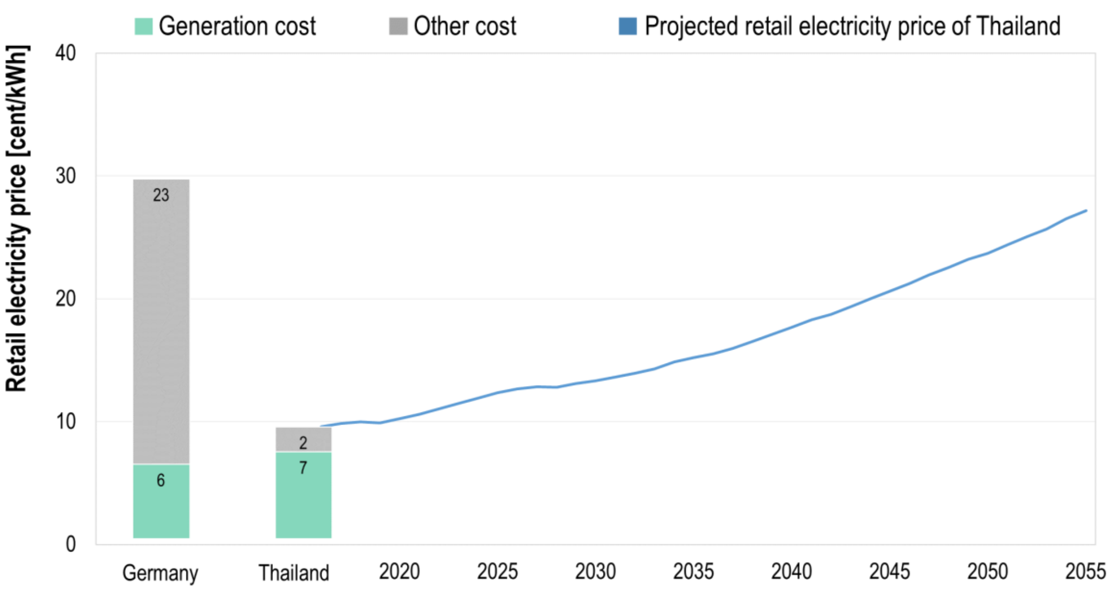


Figure 6.4 Projected retail electricity price in Thailand

6.5 Global cost calculation (Macroeconomic perspective)

Thailand does not have an economic evaluation guideline for the energy system in the building, therefore this study follows the global cost procedure according to the EN15459. There are two financial calculation approaches: microeconomic and macroeconomic. The macroeconomic aspect includes carbon dioxide costs and excludes taxes, value-added tax (VAT), charges, and subsidies, while the microeconomic aspect includes taxes, VAT, and charges, but excludes carbon dioxide costs (EC, 2012).

This research aims to assess the environmental impact; therefore, the macroeconomic perspective is selected for the assessment. The global cost calculation is shown in Eq. 6.4. The lifetime of the building is defined as 50 years. The discount rate for the calculation in this study is 0.54%.

$$C_g(\tau) = C_I + \sum_j \left[\sum_{i-1}^{\tau} \left(C_{a,I}(j) \times R_d(i) \right) + C_{c,i}(j) - V_{f,\tau}(j) \right] \qquad \text{(Eq. 6.4)}$$

where:

T	: calculation period
$C_g(\tau)$	: global cost over the calculation period
C_I	: initial investment cost for set of measure j
$C_{a,I}(j)$	: annual cost during year i for the set of measure j
$C_{c,i}(j)$	: carbon dioxide cost for the set of measures j during year i
$V_{f,\tau}$	: residual value of set of measure j at the end of the calculation period (discounted to the starting year)
R_d	: discount factor for year i based on the discount rate r
p	: number of the year from the starting period
r	: real discount rate
i	: inflation rate
k	: real interest rate

6.5.1 Investment cost assumption for integrated technology in building

The integrated technology options in Chapter 4 are taken into consideration for the global cost assessment. The cost assumptions are referenced from the several sources in Table 6.3 (EGS, 2016; Agora, 2015; IRENA, 2017; STIEBEL, 2016; TESLA, 2017; Fraunhofer ISE, 2019). The global cost assessment consists of two main costs: fixed cost (i.e. structural element) and variable cost (i.e. the different elements between scenarios).

Table 6.3 Investment cost assumption for global cost calculation

Detail	Value	Unit	Lifetime (Years)	Maintenance (%)	Source
Energy efficiency measures (EEM)					
Insulation	39	EUR/m²	50	0.5	EGS 2016, EC, 2012
Shading	33	EUR/m²	50		
Double glazing window	33	EUR/m²	50		
PV system					
PV system (2016)	1,255	EUR/kWp	20	1.0	EGS 2016, Fraunhofer ISE 2019, EC, 2012
PV system (2037)	829	EUR/kWp	20		
PV system (2057)	659	EUR/kWp	20		
Ice thermal energy storage (ITES) system (70 kWh)					
ITES system (2016)	151	EUR/kWh	20	2.0	EGS 2016, STIEBEL 2016, EC, 2012
ITES system (2037)	109	EUR/kWh	20		
ITES system (2057)	79	EUR/kWh	20		
Battery energgy storage (BES) system (14 kWh)					
BES system (2016)	434	EUR/kWh	10	1.0	TESLA 2017, IRENA 2017
BES system (2037)	173	EUR/kWh	10		
BES system (2057)	72	EUR/kWh	10		

The PV system is assumed at 1,255 EUR/kWp with a cost reduction rate of 1.5% per year (Fraunhofer ISE, 2019). The ice thermal energy storage system cost is retrieved from the real implementation in Bangkok, which is approximately 151 EUR/kWh, and the projected cost reduction of 1.3% per year (STIEBEL, 2017). The battery energy storage (BES) system cost is approximately 434 EUR/kWh, which is referenced from the commercial product (TESLA, 2017). The BES cost reduction is projected at 4% per year (IRENA, 2017). The BES system cost is higher than the ITES system by almost triple. The optimistic rapid cost reduction of the BES would attract homeowners for future deployment.

6.5.2 Carbon dioxide price

This study assumes the carbon dioxide price of the EU context at 20 EUR per tonne of CO_2 until 2025, 35 EUR per tonne of CO_2 until 2030, and 50 EUR per tonne of CO_2 beyond 2030 (EC, 2012).

6.6 Global cost assessment

In Figure 6.5, the reference residential building (REF) of the Grid scenario has the highest global cost of 1,316 EUR/m^2. The major cost is the energy cost which accounts for 928 EUR/m^2, or equivalent to 71% of the total global cost. Generally, the consumer only considers the purchase cost in the decision-making process for purchasing a detached single-family house, which does not cover the life cycle energy cost of the building use. The nearly zero energy building (nZEB) building with energy efficiency measures (EEM), such as insulation, double-glazing windows, and shading, has a global cost of 1,069 EUR/m^2, or 19% lower than the REF building. Only the EEM can reduce the energy cost to a great extent by 36% compared to REF building.

The interesting findings show that implementing the EEM in the building results in lower global costs compared to installing the PV system on the roof. This is because of the mismatch between PV generation and energy demand behavior in the residential building. Rather than only installing the PV system on the roof, the energy design in the building should be optimized with cost and benefit to reduce the energy expenditure in the building.

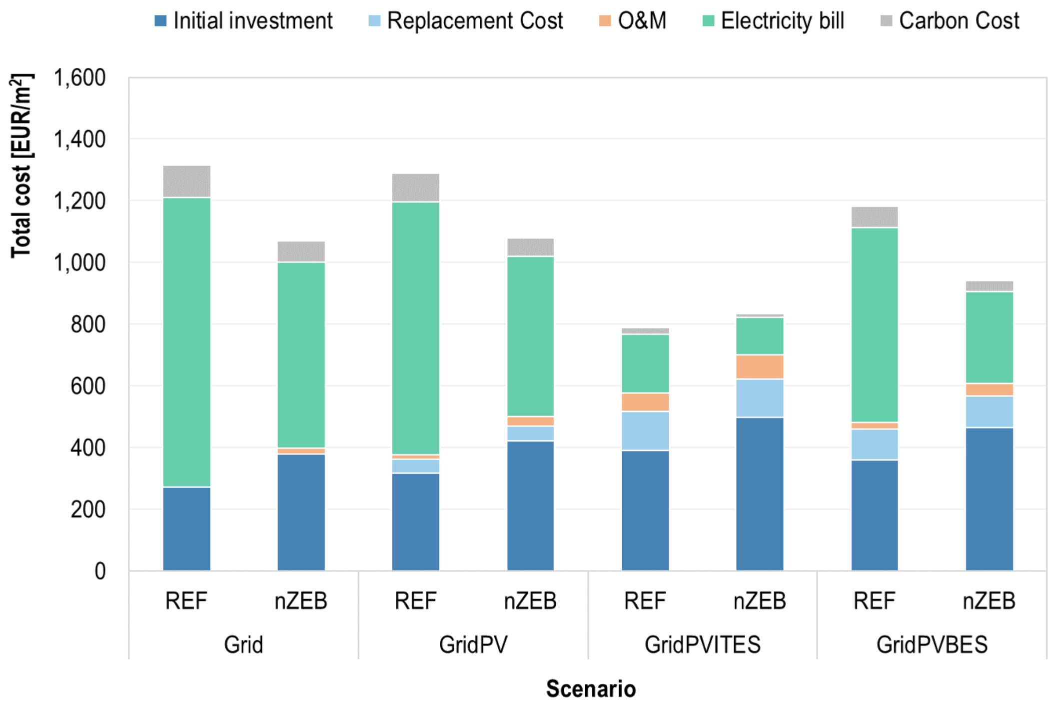


Figure 6.5 Global cost comparison

The energy storage system can increase the PV direct use in the residential building. As the cooling energy demand is the main energy expense for Thai households, the REF building with the ice thermal energy storage (ITES) system (GridPVITES scenario) results in the lowest global cost of 789 EUR/m^2, while nZEB building under the same scenario has a global cost of 835 EUR/m^2 because of the EEM investment costs. It should be remarked that the nZEB building in the GridPVITES scenario has the lowest energy cost of 120 EUR/m² compared to other scenarios (Table 6.4). The maintenance cost of the ITES system is higher than the battery energy storage (BES) because the ITES system requires a skilled technician for maintenance of equipment such as insulation, pipes, and fan coil units. The capacity of technical building personnel is highly required for future commercial-scale development in Thailand.

Table 6.4 Total cost embodied by scenario (EUR/m²)

Parameter/ scenario	General cost	EEM	PV	ITES	BES	CO_2	Replac ement	O&M	Energy cost	Total cost
Grid										
REF	273	0	0	0	0	106	0	0	938	1,316
nZEB	273	106	0	0	0	68	0	18	604	1,069
GridPV										
REF	273	0	43	0	0	93	47	13	821	1,289
nZEB	273	106	43	0	0	59	47	32	520	1,079
GridPVITES										
REF	273	0	43	75	0	22	126	59	192	789
nZEB	273	106	43	75	0	14	126	78	120	835
GridPVBES										
REF	273	0	43	0	43	71	102	21	629	1,183
nZEB	273	106	43	0	43	34	102	40	300	940

The REF building with the BES system (GridPVBES scenario) has a higher global cost than the ITES system. This is because the BES system needs almost three times of the investment cost than the ITES system. The higher the BES capacity, the higher the global cost. Although the BES system can reduce the energy expense compared to the REF building, the BES system is required to be replaced every ten years due to the battery's lifetime. The integration of the EEM into the PV system with and without the BES system (nZEB in the GridPVBES scenario and nZEB in the GridPV scenario) is the more attractive option compared to the REF building in the GridPVBES scenario.

In reality, the consumer cannot obtain the life cycle cost breakdown from the housing development company when purchasing a house in Thailand. Normally, large-scale real estate companies develop the house with the same design and infrastructure in the same area by optimizing the investment cost and selling cost for maximum profit. The individual consumer can have the energy design in the building but has to face the expensive cost from the housing development company (e.g. design cost, material, labor). The energy design concept for detached family houses in Thailand can first be introduced through a voluntary program and then enforced by the energy standard. The voluntary program can increase consumer awareness on energy efficiency while preparing the proper energy standard for the real estate company for future enforcement.

6.7 Carbon dioxide emissions cost

The environmental impact from each scenario is assessed in monetary terms by using the carbon dioxide cost. The REF building in the Grid scenario has the highest energy cost from the national electricity grid, therefore it has the highest carbon dioxide cost of 106 EUR/m^2, while the nZEB building in the GridPVITES scenario pays only 14 EUR/m^2 at the end of the building's lifetime (Figure 6.6). The carbon dioxide cost is directly correlated to the amount of imported electricity from the electricity utility. Only the EEM implementation can reduce the carbon dioxide cost by 36% compared to the REF building in the Grid scenario. The integration of the ice thermal energy storage system can reduce the carbon dioxide cost by 88%, while the BES can provide savings of 68% compared to REF building in Grid scenario. The energy efficiency measure implication plays a significant role in carbon dioxide cost reduction.

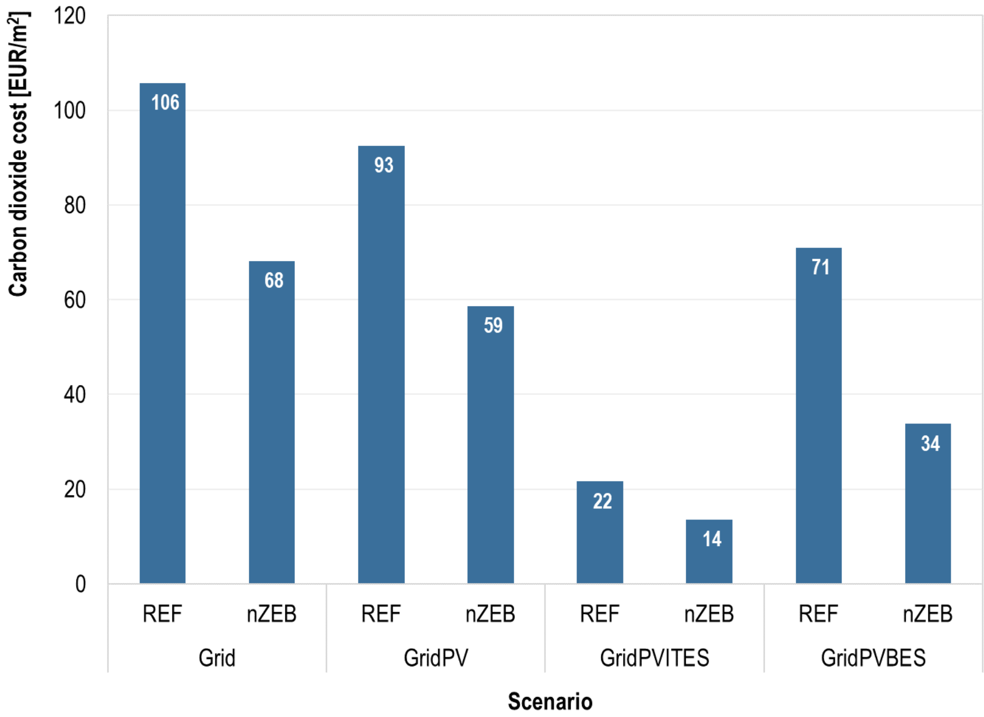


Figure 6.6 Carbon dioxide cost assessment

Although the carbon dioxide cost is not the major embodiment of the global cost compared to the energy cost, it should be taken into consideration for the decarbonization of the building sector. Some studies indicate that the environmental concerns would raise the energy efficiency awareness for the consumer (Chau et al., 2010; Sammer & Wüstenhagen, 2006). The environmental impact can also play a vital role in drawing the consumer's attention towards energy label enforcement in Thailand with intelligible information.

6.8 Net present value (NPV) assessment

This research also evaluates the net present value (NPV) for a package of integrated technology measures in the detached single-family building. The NPV indicates a profitable investment of the package where a positive NPV (NPV>0) implies that it is economically advantageous. On the other hand, a negative (NPV<0) indicates the economically non-advantageous situation of the project. The higher the NPV, the higher the economic benefit. The NPV evaluation takes the costs and benefits during the project's lifetime into account. The energy sold from the excess PV generation and gained value are considered as the benefits of the project which depend on the electricity rate the consumer pays. The internal rate of return (IRR) is the discount rate that results in an NPV equal to zero. The greater the IRR, the more profitable an investment is.

Figure 6.7 shows the NPV assessment of each measure combination in the detached single-family building. Only the ice thermal energy storage (ITES) scenario is a profitable option for investment with an NPV of 15,592 EUR (IRR 1.3%) and 31,160 EUR (IRR 1.7%) for the REF and nZEB building, respectively. All the other scenarios (Grid, GridPV, and GridPVBES) have a negative NPV, which implies a non-profitable investment because the non-ITES scenarios have a high amount of imported electricity to meet the cooling demand in the building, while the ITES system requires less imported electricity. The outflow cash of the ITES scenario is higher than the inflow cash at the end of project's lifetime, hence the NPV is negative and vice versa.

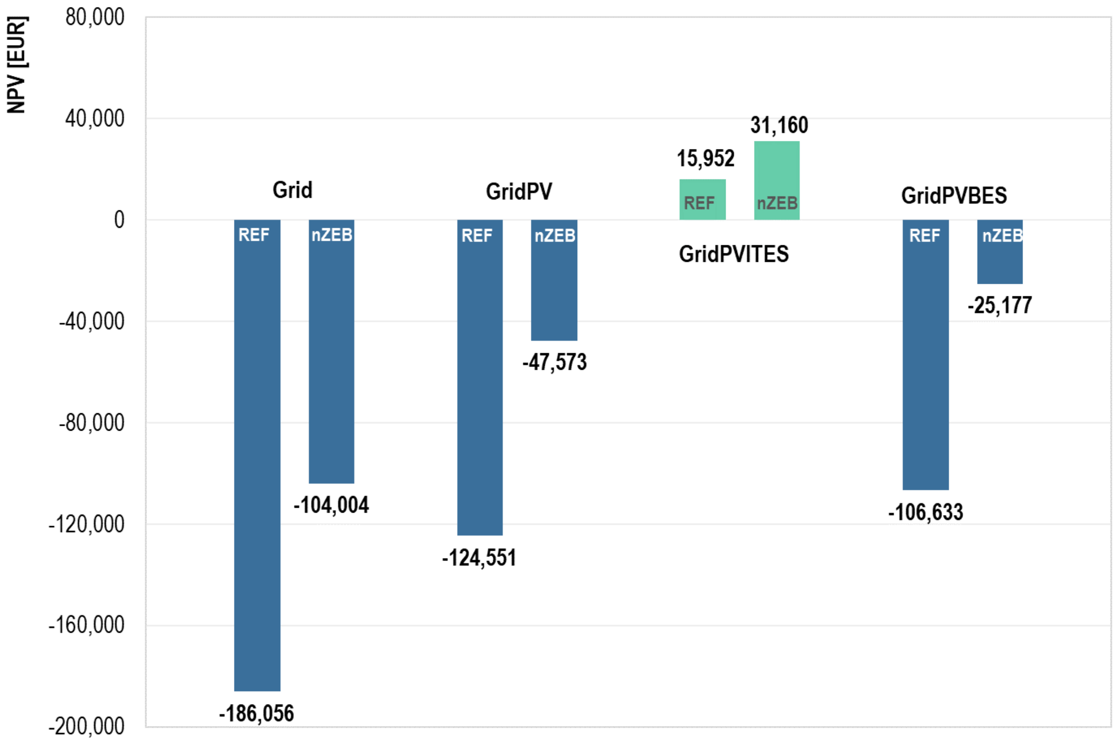


Figure 6.7 Net present value of different scenarios under the net metering program

6.9 Net present value sensitivity analysis

6.9.1 Discount rate variation

The NPV sensitivity analysis with the discount variation is shown in **Error! Reference source not found.**, Table 6.6, and Table 6.7. The number in the bracket represents a negative value of NPV. At a discount rate of up to 1.0%, the ITES scenario is still the profitable option with and without an incentive program from selling excess electricity. At the higher discount rate of 3% without the incentive support, the NPV results in no profit for all scenarios. The higher discount rate results in a lower NPV because the initial investment remains unchanged, while the future benefit is reduced by the higher discounted factor. In other words, lower discount rates result in a higher NPV. The ITES case become less favorable when the higher discount rate is applied, but it does not change the fact that the ITES option is still the most attractive among other options.

Table 6.5 Net present value sensitivity analysis by discount rate at 0.54%

Scenario	**Building Type**	**NPV at discount Rate 0.54% (EUR)**		
		Net metering	**Net billing**	**Non-incentive**
Grid	REF	(186,056)	(186,056)	(186,056)
	nZEB	(104,004)	(104,004)	(104,004)
GridPV	REF	(124,551)	(151,126)	(162,541)
	nZEB	(47,573)	(77,525)	(90,391)
GridPVITES	REF	**15,952**	**6,450**	**2,369**
	nZEB	**31,160**	**13,579**	**6,028**
GridPVBES	REF	(106,633)	(113,747)	(116,803)
	nZEB	(25,177)	(32,688)	(35,915)

Table 6.6 Net present value sensitivity analysis by discount rate at 1.0%

Scenario	**Building Type**	**NPV at discount Rate 1.0% (EUR)**		
		Net metering	**Net billing**	**Non-incentive**
Grid	REF	(167,574)	(167,574)	(167,574)
	nZEB	(97,778)	(97,778)	(97,778)
GridPV	REF	(115,721)	(137,727)	(147,962)
	nZEB	(50,478)	(75,290)	(86,826)
GridPVITES	REF	**6,026**	(1,845)	(5,505)
	nZEB	**17,067**	**2,503**	(4,267)
GridPVBES	REF	(99,992)	(105,885)	(108,625)
	nZEB	(30,732)	(36,954)	(39,847)

Table 6.7 Net present value sensitivity analysis by discount rate at 3.0%

Scenario	Building Type	NPV at discount Rate 3.0% (EUR)		
		Net metering	Net billing	Non-incentive
Grid	REF	(114,693)	(114,693)	(114,693)
	nZEB	(79,897)	(79,897)	(79,897)
GridPV	REF	(87,028)	(99,321)	(106,039)
	nZEB	(54,924)	(68,779)	(76,352)
GridPVITES	REF	(20,573)	(24,968)	(27,370)
	nZEB	(20,438)	(28,570)	(33,015)
GridPVBES	REF	(79,632)	(82,922)	(84,721)
	nZEB	(45,152)	(48,626)	(50,525)

6.9.2 Incentive program options

The net billing program is another incentive scheme for buying electricity from renewable energy projects. The net billing program is similar to the net metering program but only the rate is different. The rate of the net metering program is equal to the retail electricity price, while the rate of the net billing program is lower than the retail electricity price. The retail electricity price is simply defined as equal to the wholesale electricity price. Currently, Thailand has neither implemented the net metering nor the net billing program for residential prosumers. The NPV sensitivity analysis of the incentive programs can provide information for future incentive program deployment.

This research assumes the net billing rate is equal to the wholesale electricity price which is estimated in Section 6.3. According to the net metering program consideration, only the ice thermal energy storage (ITES) option has a positive NPV by taking a higher buying rate into account. It can simply be foreseen that a non-ITES scenario would have the same result with a negative NPV under the net billing program, which has a lower rate than the net metering program.

The results show that the GridPVITES scenario under the net billing program still has a positive NPV but less profit than the net metering program, as expected. The meaningful result illustrates that the ITES system investment is worth the investment even with the lower buying rate under the net billing program (Figure 6.8). The main advantage of ITES is economically advantageous because of the reduction of the buying amount of electricity from the grid.

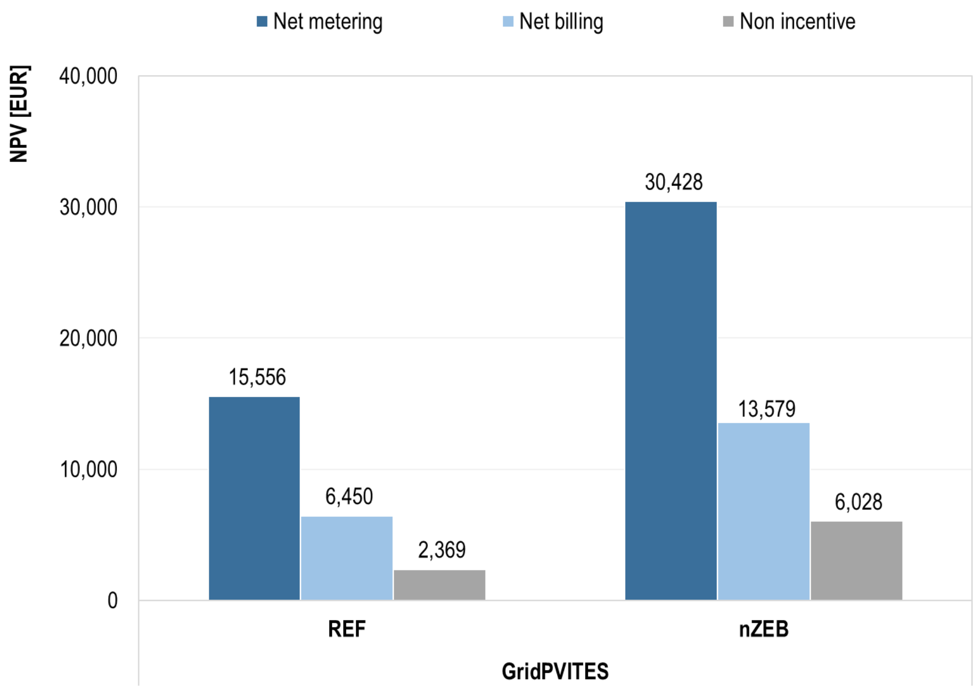


Figure 6.8 NPV evaluation under the incentive and non-incentive program of the GridPVITES scenario at a discount rate of 0.54%

6.9.3 Electricity price development

The retail electricity price in Thailand increases by an average of 3% per annum. The retail electricity price variation is assessed with high and low electricity price developments to foresee whether ITES is still a profitable option. This research assumes that the low electricity price case increases by 1.5% per year, while the high electricity price case is assumed at 6% per year. The results show that the ITES system is still an attractive investment option under the low and the high electricity price (Table 6.8).

Table 6.8 Net present value sensitivity analysis by the energy price development

Scenario	Building Type	NPV, discount rate at 0.54% (Net metering)		
		Reference	Low development	High development
Grid	REF	(186,056)	(188,045)	(190,034)
	nZEB	(104,004)	(126,595)	(127,534)
GridPV	REF	(124,551)	(104,578)	(105,151)
	nZEB	(47,573)	(48,414)	(48,007)
GridPVITES	REF	**15,952**	**16,930**	**18,303**
	nZEB	**31,160**	**32,272**	**34,116**
GridPVBES	REF	(106,633)	(107,462)	(107,996)
	nZEB	(25,177)	(24,616)	(23,743)

The remarkable finding is that GridPVITES is more attractive when the electricity price increases because it does not require a high amount of imported electricity, unlike the other scenarios. In addition, it makes more profit by selling excess PV to the grid under the net metering program with the same rate of the retail electricity price.

6.10 Consumer behavior of buying detached single-family house with integrated technology

6.10.1 Introduction of choice based conjoint (CBC)

The results have revealed that the combination of the energy efficiency measures (EEM), PV system, and the ice thermal energy storage (ITES) system is the most favorable integrated technology package for a detached single-family house both in the technical and economic aspects. Interesting questions arise on whether the Thai consumer is interested in buying these technologies for a detached single-family house if it is available in the market, and how much their willingness to pay (WTP) is.

In everyday life, the consumer usually makes the trade-off between products/services in the decision-making process. A choice-based conjoint (CBC) offers a quantitative measurement to determine the individual preference between the choice set (Mangham, 2008). Some studies refer to the CBC with the term of Discrete Choice Experiment (DCE) (Louviere et al., 2010). The CBC method is widely used in economic health research to identify health services and products. In marketing, the CBC is used to define the consumer preference and willingness to pay for their products with a similar product from competitors. The CBC is not only limited to health and marketing research, but is also used broadly in the energy economic context, such as the investigation of the WTP for green building, decisions on retrofit building, and the influence of eco-labeling in building (Sammer & Wüstenhagen, 2006; Chau et al., 2010; Galassi & Madlener, 2017). The CBC is useful for designing new energy policy inventions which can answer specific information, e.g. how much one is the willing to pay when integrating insulation into a building.

This research aims to examine the consumer likelihood of buying integrated technology for a detached single-family house in Bangkok by using the insightful results from technology and economic assessments together with an in-depth interview (see Section 7.3) to help design the choice set (attributes and levels). The investigation is based on the assumption that energy labels are available and indicate the energy consumption in monetary terms, and also how the consumer makes the trade-off between energy costs and purchase cost when buying a detached single-family house with a different package of integrated technology measures. The WTP estimation is retrieved from the state preference by conducting a consumer survey (Breidert et al., 2006). The WTP can address the energy policy strategy and required incentive support to accelerate the demand for high technology packages in detached single-family houses in Thailand.

6.10.2 Attribute and level design

This research focuses on the detached single-family house with several integrated technology packages. A model of a detached single-family house is built according to the individual owner's requirements or the real estate company's development direction. The choice set in the survey consists of technology measures (known as an attribute) which are formed together with the purchase cost and energy costs (Table 6.7).

Table 6.9 Attributes and levels in the choice based conjoint (CBC)

Attribute	Level
Insulation	Yes No
Rooftop PV	Yes No
Energy storage	Yes No
Monthly energy cost	25 EUR/month 50 EUR/month 70 EUR/month 80 EUR/month 100 EUR/month 130 EUR/month
Purchase cost	450 EUR/m^2 500 EUR/m^2 550 EUR/m^2 600 EUR/m^2 650 EUR/m^2 700 EUR/m^2
None	-

The levels of each attribute are retrieved from the economic assessment. The attributes and their levels are combined as a choice set for the respondent to make the decision as shown in Table 6.8. The choice set consists of two alternatives and a none option to reflect the real-world situation if the respondent is not satisfied with the two alternatives in the choice set.

Table 6.10 Example of choice based conjoint question

Attribute/Alternative	Alternative 1	Alternative 2	Alternative 3
Energy efficiency measures	Yes	No	I don't choose either of the alternatives
Rooftop PV	No	No	
Energy storage	No	No	
Monthly energy cost (EUR/month)	70	130	
Purchase cost (EUR/m^2)	550	450	
Your choice	☐ **Choose**	☐ **Choose**	☐ **Choose**

6.10.3 Sample size and survey

The typical sample size of the CBC is approximately 150 to 1,200 respondents (Sawtooth, 2010). There were 827 respondents that participated in the survey via face-to-face interviews in this research. The survey was conducted in Bangkok, Thailand in 2018. The main respondents have a medium and high income and have the likelihood of buying a house in the future (see Table 6.11). The interview took approximately 10 minutes per respondent.

Table 6.11 Social demographic of the choice based conjoint (CBC)

Characteristic	Percent	Characteristic	Percent
Gender		**Occupation**	
Male	50%	Temporary employment	4%
Female	50%	Employee in government	60%
		Employee in company	14%
Age		Business owner	21%
20-30	27%	Retirement	1%
31-40	45%		
41-50	27%	**Family size**	
51-60	1%	1-2 persons	32%
		3-4 persons	52%
Education		5-6 persons	13%
Secondary	5%	> 6 persons	3%
Vocational	22%		
Bachelor	62%	**Building type of respondent**	
Master	11%	Single family home	44%
		Apartment/condominium	30%
Household Income		Townhouse	14%
< 600 EUR	9%	Commercial building	5%
601-1,250 EUR	31%	Rented room	7%
1,251-1,875 EUR	29%		
1,876-2,500 EUR	17%	**Likelihood of buying in the future**	
2,501-3,750 EUR	12%	Single family home	72%
> 3.750 EUR	2%	Condominium	4%
		Townhouse	5%
		Shophouse	3%
		No	16%

The target respondent has a middle to high-income and is likely to buy a detached single-family house in the future. The middle-income group has a total salary between 601 to 1,875 EUR per month - working mainly in a private company or a governmental agency. The typical family size of the respondent is between 3-4 persons. The main respondents are currently living in detached single-family houses. The ownership status of the building indicates that more than half of the respondents are either the tenants or are occupants who are likely to buy their own house in the future. The respondents were asked to choose the two alternatives of the detached single-family house with an area of 140 m^2 at the same location and the same exterior and interior perspective, but different technology features in the detached single-family house. It should be noted that the purchase cost is not included in the interior design. The data collection was paper-based and filled in through the Sawtooth software for WTP calculation.

6.10.4 Model estimation

In the decision-making process over the product or service, the person has "latent utility" which cannot be captured by physical measurement. The CBC analysis is based on the Random Utility Theory (RUT) where the consumer will choose the product with a latent utility (U_{ia}) which consists of the stochastic component (V_{ia}) and the unobserved factor, or random component (ε_{ia}) (Eq. 6.5). There are several models to estimate the consumer preference by performing different conditions for the unobserved factor (Train, 2002). The standard logit model can capture the systematic preference variation while the mixed logit model allows the random preference variation and the correlation of unobserved factors with the other choices, which is more flexible than the standard logit. (Galassi & Madlener, 2017; Min, 2014; Audibert et al., 2013)

$$U_{ia} = V_{ia} + \varepsilon_{ia} \qquad \text{(Eq. 6.5)}$$

$$R_{kl} = \frac{\max(\beta_{kl}) - \min(\beta_{kl})}{\Sigma_{k=1}^{5}(\max(\beta_{kl}) - \min(\beta_{kl}))} \qquad \text{(Eq. 6.6)}$$

$$WTP_{kl} = \left(\frac{\max(p_{kl}) - \min(p_{kl})}{\max(\beta_{kl}) - \min(\beta_{kl})}\right) \times \beta_{kl} \qquad \text{(Eq. 6.7)}$$

where:

R	: relative importance
β	: part-worth utility
k	: attribute, $k \in \{1,2,3,4,5\}$
l	: level $l \in \{1,\ldots l_k\}$
V_{ia}	: deterministic component
ε_{ia}	: stochastic component
WTP	: willingness to pay
p	: price attribute (EUR)

The Hierarchical Bayes (HB) method can reveal individual preferences by borrowing the information from other consumers to stabilize the individual utility value (Sawtooth, 2000; Eisen-Hecht et al., 2004; Kaufmann et al., 2013). This research uses the robust ability of the HB approach to estimate the relative importance of the attribute and part-worth utility for individual preferences by using the Sawtooth software which can compute the complexity of the data. The importance of the relative attribute (R) and willingness to pay (WTP) can be calculated from Eq. 6.6 and Eq. 6.7, respectively.

In reality, each consumer has an individual taste in making choices. The individual utility value can provide a specific preference based on the choice information rather than assuming a homogenous preference for all consumers. The part-worth utility is a numeral score to indicate the importance of each level associated with other levels of within each attribute which influenced a consumer's decision. The part-worth utility score is calculated from dummy coding, and the sum of part-worth utility within an attribute is equal to zero (Sawtooth, 2000). A simple calculation of part-worth utility and the importance of the attributes is shown in Figure 6.9.

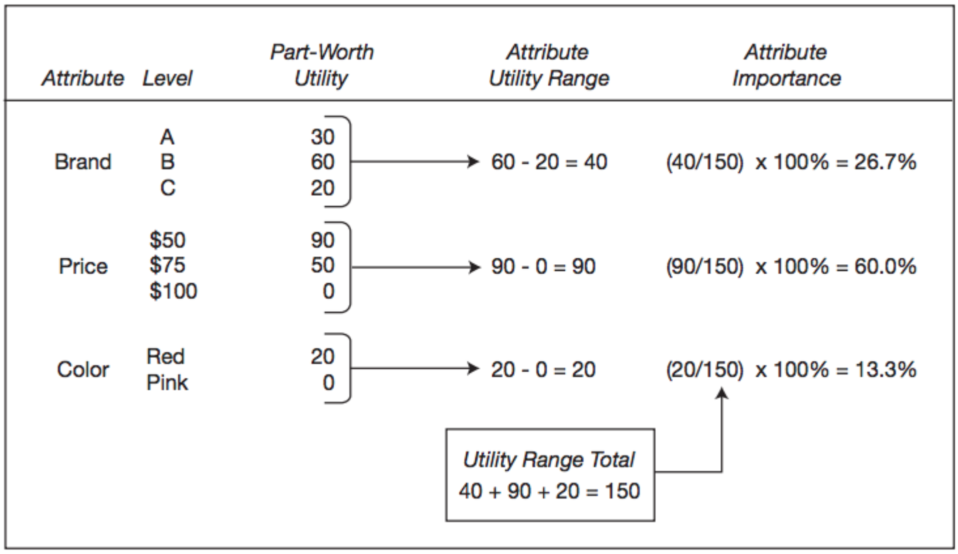


Figure 6.9 Simple calculation of part-worth utility and importance (Sawtooth, 2000)

For example, a consumer has to choose a product by considering three attributes and its associated level, which are brand (A, B, C), price ($50, $75, $100), and color (Red and Pink). The result can be interpreted that the consumer considers the price factor as the most important factor (with the highest score of attribute importance) in making a decision, compared to brand and color. The consumer is likely to choose brand B with a red color for $50. The part-worth utility with the highest score strongly indicates preference for the decision of each attribute.

6.11 Empirical results and discussion on the willingness to pay

6.11.1 Importance of the attribute for making a choice

Table 6.12 shows the part-worth utility of each attribute and level. The higher the value of part-worth utility, the higher the preference over another.

Table 6.12 Attributes and levels in the choice based conjoint (CBC)

Attribute	Level	Part-worth utility
Insulation	Yes	53.46
	No	-53.46
Rooftop PV	Yes	30.99
	No	-30.99
Energy storage	Yes	21.13
	No	-21.13
Monthly energy cost	25 EUR/month	20.06
	50 EUR/month	45.69
	70 EUR/month	22.69
	80 EUR/month	2.87
	100 EUR/month	-64.77
	130 EUR/month	-26.53
Purchase cost	450 EUR/m^2	30.47
	500 EUR/m^2	38.45
	550 EUR/m^2	10.09
	600 EUR/m^2	40.55
	650 EUR/m^2	-48.85
	700 EUR/m^2	-70.72
None	-	-1.25

The results show that among the five attributes, the respondents choose energy cost as the most important quality for purchasing a detached single-family house, followed by purchase price, insulation, external shading, rooftop PV, and energy storage, respectively (Figure 6.10).

An interesting finding is consumers are more concerned with the energy cost rather than the purchase cost if the energy cost information is available when making the decision. In other words, the consumer makes the trade-off between energy cost and purchase cost and then the availability of technical measures. Very low importance is placed on the energy storage system, as it can be assumed that the consumer is not as familiar with it as compared with the insulation and PV system.

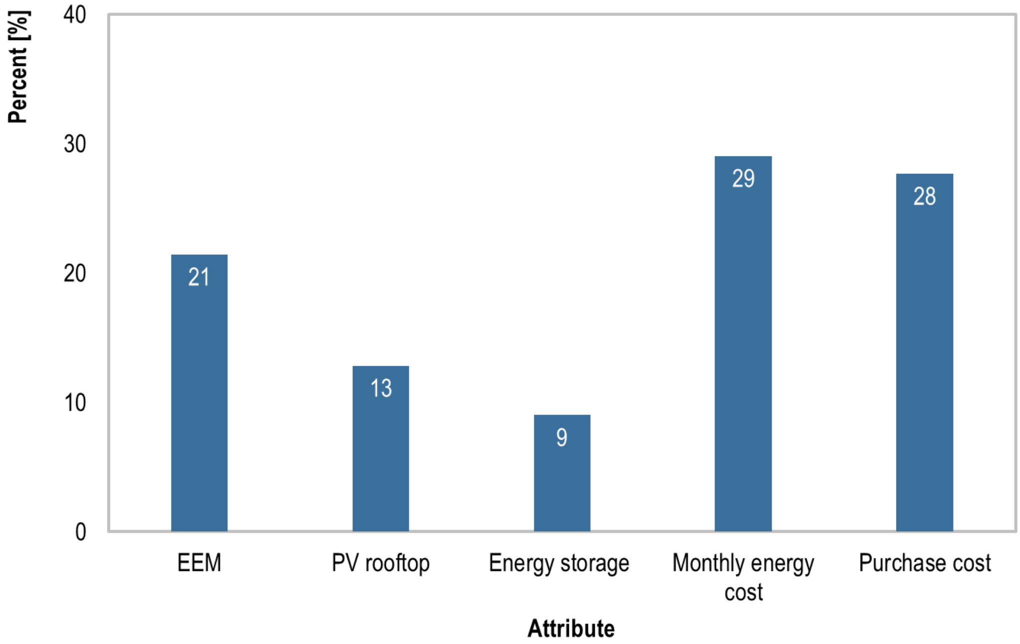


Figure 6.10 Importance of each attribute from consumer survey

In reality, the consumer is concerned with the living expense which covers the energy cost. The purchase cost of the detached single-family house does not provide the estimated energy cost information. The result of the survey has revealed a realistic situation where the consumer makes a choice that is correlated to living expenditures. The energy consumption can be interpreted in terms of monetary value in the energy label to increase consumer knowledge on the life cycle cost consideration, rather than the initial purchase cost. However, it should be made aware that the energy label provides information based on technical assessments where, in reality, energy consumption is correlated with technical and non-technical dimensions, such as individual consumer preference on buying an electric appliance, thermal comfort, background knowledge, and daily activity.

6.11.2 Willingness to pay (WTP) for the integrated technology package

The willingness to pay (WTP) defines the consumer preference for the incremental cost of additional features compared to the reference case. In this study, the reference building refers to a building without insulation, a PV system, and energy storage. The part-worth utility of each attribute is shown in Table 6.12. The higher the value of part-worth utility, the higher the preference to choose that choice. The purchase cost of the reference building is assumed to be at 450 EUR/m^2 based on the average market price in Bangkok. The WTP estimation of integrated technology is calculated from Eq. 6.7 by using the price attribute and part-worth utility from the Table 6.10. For example, the calculation for WTP of energy efficiency measures integration is shown below.

$$WTP_{kl} = \left(\frac{\max(p_{kl}) - \min(p_{kl})}{\max(\beta_{kl}) - \min(\beta_{kl})}\right) \times \beta_{kl}$$

$$= \frac{(700 - 450)(\mathrm{EUR/m^2})}{30.47 - (-70.42)} \times 53.46 = 132\ \mathrm{EUR/m^2}$$

The general construction cost without energy efficiency measures is approximately 450 EUR/m^2. The results reveal that the WTP for the energy efficiency measures in a detached single-family house is approximately 132 EUR/m^2, while the WTP of the PV system and energy storage is approximately 77 EUR/m^2 and 52 EUR/m^2, respectively (Figure 6.11). For example, the respondents have willingness to pay the detached single-family house with the energy efficiency measures at 582 (450+132) EUR/m^2.

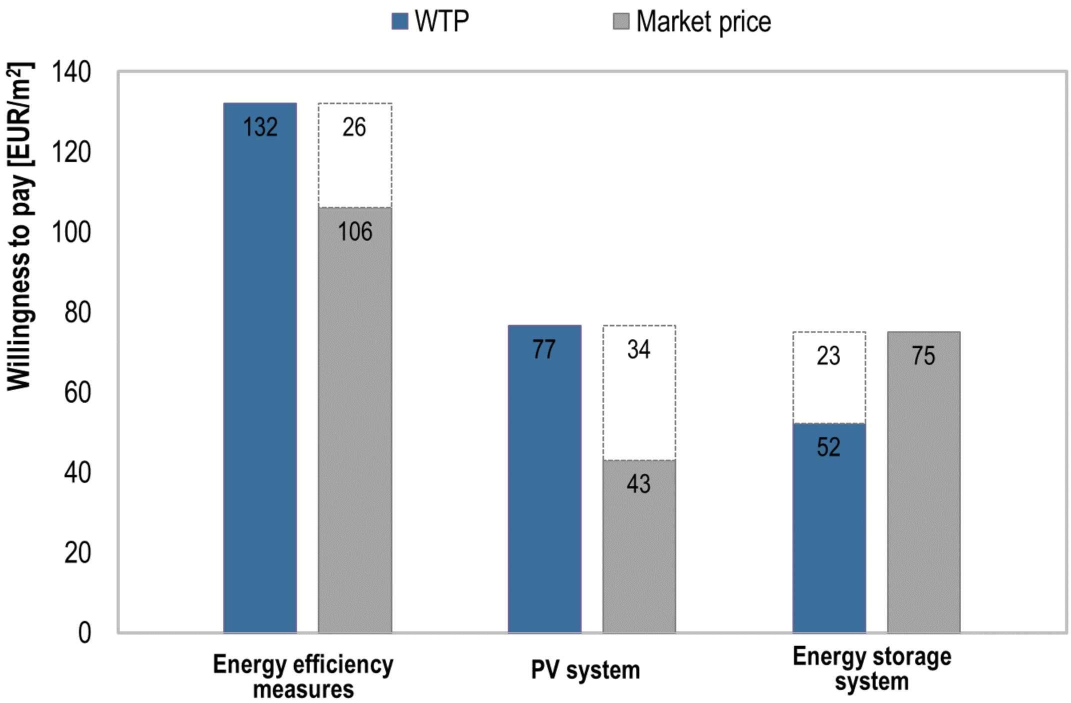


Figure 6.11 Willingness to pay and market price for each energy feature in a residential single-family building

The degree of willingness to pay for the energy efficiency measures (EEM) is higher than the PV system and energy storage because of the trade-off between the purchase cost and energy costs of each technology measure. It is correlated with the relative importance of each attribute as mentioned in Section 6.11.1. Comparing the WTP and market price of each feature, the EEM and the PV system measures have a potential on the commercial scale, as the WTP is higher than the market price. In other words, the housing development agency can introduce the residential single-family house with the integration of the EEM and 5 kWp PV systems with a margin of 60 (26+34) EUR/m^2. The government can promote the importance of the EEM integration in the building by highlighting the energy cost reduction through the energy standard and label.

The WTP of a fully integrated technology package in a detached single-family building (EEM, PV, and energy storage system) is approximately 711 (450+132+77+52) EUR/m^2, which is 58% higher than the reference building. For the energy storage system, the WTP is lower than the market price. The future cost reduction and an incentive program would encourage more WTP for the energy storage system and PV in a detached single-family house.

6.12 Conclusion

The technical assessment has proven the energy performance of the technology measures combinations for the residential building. The economic assessment provides the investment cost decision of different integrated technology packages. Generally, the purchase cost of a detached single-family house alone gives misleading data to the consumer as it excludes the energy cost. The economic assessment can illustrate the life cycle investment which includes energy cost in the calculation.

The summary of the economic assessment for each scenario is shown in Table 6.13. The economic assessment shows that the energy cost accounts for 70% of the total global cost. The consumer must bear the high energy cost from the poor energy design of the building until the end of its lifetime. Energy efficiency measures (EEM) is an essential technology measure for the residential building which has a large potential for reducing energy cost by 36% compared to the reference (REF) building. The energy cost of the EEM implementation is 26% lower than installing only the PV system due to the mismatch between PV generation and energy demand in the building.

Table 6.13 Comparison of energy performance and lifetime cost of the building for each scenario

Scenario	Grid		GridPV		GridPVITES		GridPVBES	
Type of building	**REF**	**nZEB**	**REF**	**nZEB**	**REF**	**nZEB**	**REF**	**nZEB**
Electricity demand [kWh/(m^{2}a)]	111	111	111	71	55	37	111	71
CO_2 emissions [kg of CO_2/(m^{2}a)]	55	36	48	31	11	7	37	18
Lifetime cost [EUR/m^2]	1,316	1,069	1,289	1,079	789	835	1,183	940
Energy cost [EUR/m^2]	938	604	821	520	192	120	629	300
CO_2 cost [EUR/m^2]	106	68	93	59	22	14	71	34

The most favorable investment option is the efficient building equipped with the PV and ice thermal energy storage systems (ITES). The additional cost for the ITES system results in lower energy costs compared to the REF building. This is because the ITES can provide cooling energy during the nighttime by storing PV generation during the daytime. Consequently, the imported electricity from the grid decreases along with the carbon dioxide emissions costs. The battery energy storage (BES) system can become an attractive investment option if the battery system cost is cheaper in the future.

Considering the revenue of selling excess electricity from the PV system, the ITES system integration is the only profitable option with and without net metering or net billing programs (net present value is positive). In other words, the ITES investment with PV system in the residential building is economical advantageous because of its technology performance characteristics. The prosumer with ITES will have less benefit but still positive net present value under the net billing program compared with net metering due to the buying rate of net billing being close to the wholesale electricity price.

This chapter also investigates the willingness to pay (WTP) for an integrated technology package in detached single-family buildings by conducting a consumer survey. The survey asked the respondents to choose two buildings with a different package of integrated technology by providing the purchase cost and energy cost. The meaningful results reveal that Thai consumers are concerned with energy consumption in monetary terms if it is available to them when making the decision. The consumer has willingness to pay for the EEM and PV system in the detached single-family house of 132 EUR/m^2 and 77 EUR/m^2, which is higher than the market price. It implies that the energy design concept of the EEM and PV systems in the building can be deployed on a commercial scale which benefits both consumers and real estate companies, in their point of view.

Energy policymakers should pay attention to introducing an energy policy for energy labels and enforcement for the detached single-family house in Thailand. Increasing consumer awareness of energy efficiency measures is, as well, a driving force for energy label implementation in residential buildings. A potential incentive support program could be provided through low interest home loans with integrated high potential building technologies.

- empty page -

Chapter 7

Consumer Behavior Change Invention

7.1 Introduction

Enhancing the residential sector in smart grid development has to take technology, economics, and consumer behavior into consideration. While the electricity utilities are improving the traditional electrical system to the smart grid, it should encourage the traditional consumer to be the smart consumer in the same context. The energy policy of smart technology, smart user, and smart policy nexus is a powerful driving force for sustainable smart grid development in the long-term.

This chapter proposes a new energy intervention for smart grid development in Thailand by focusing on consumer behavior. The key findings from Chapter 4 through Chapter 6 are taken into analysis, along with the stakeholder and consumer interviews in order to address the energy policy strategy to enhance the active role of the residential consumer for smart grid development in Thailand.

7.2 Methodology framework

The results of the stakeholder and consumer interviews are considered together with the key findings in Chapter 4, Chapter 5, and Chapter 6 for developing energy policy recommendations (Figure 7.1). The in-depth consumer interviews can examine consumer preference, while the stakeholder interviews can address policymakers' opinions on the smart grid development of Thailand.

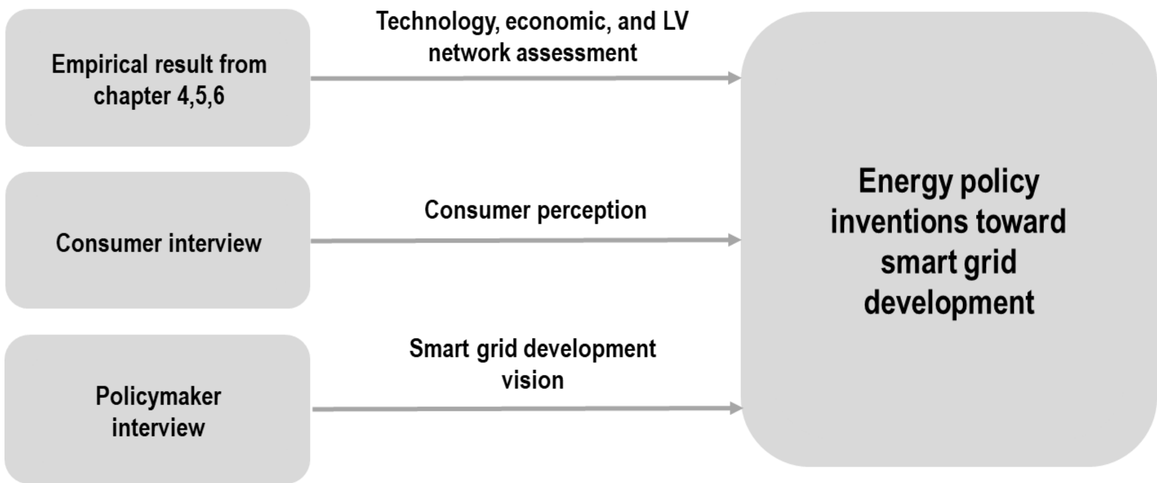


Figure 7.1 Consumer behavior gap towards smart grid research framework

The in-depth interviews with consumers and policymakers were conducted in the early stage of research to understand consumer behavior backgrounds and visions for smart grid development. The selection of the consumer interviews is based on the convenience sampling method which is simple and useful to obtain basic data. However, this method cannot represent the entire population, which is the main disadvantage of this approach. The consumer interview is conducted by open-ended and multiple-choice questions which allow the interviewees to express their understanding of the smart grid context to obtain their preferences.

The result of the in-depth consumer and policy interviews can be found in Section 7.3 and in the conference paper in Appendix 4, which can answer the research question of "What is current Thai consumer behavior and perception on the smart grid and smart meter?".

For the policymaker interviews, the selection of the interviewees is based on the snowball technique in which interviewees can refer the next potential interviewees as chain referral sampling. A semi-structured interview allows the stakeholders to freely present their opinions on smart grids. The interview questions focus on three main issues, which are 1) policy and institutional arrangement conflict, 2) consumer engagement, and 3) technology development. The result of the stakeholder interviews can answer the research questions: 1) "How is the policymaker perception in Thailand toward smart grid development under the existing electricity market?" and 2) "What are the energy policy inventions to enhance the traditional consumer to become a proactive consumer?".

7.3 Consumer behavior perception towards smart meter

Smart grid technologies are diverse and can be divided into two areas: the electricity supply system and the end user. The most widespread technology at the end user is the Advanced Meter Infrastructure (AMI), also known as a smart meter. Currently the smart meter is not yet implemented in the residential sector. The "smart" term can be misleading and lead the consumer to have over-expectations from the smart meter, e.g. helping them save energy costs by doing nothing. The consumer interviews show that the Thai consumer still lacks understanding of the smart meter's advantages by having over-expectations that the smart meter can help them reduce electricity costs. The electric utility must take serious action on providing basic knowledge of the smart meter's main advantages to the consumer to avoid uncertain opposition of smart meter adoption, e.g. privacy concerns and overestimation of technical advantages.

The smart meter is a useful device for the electric supplier and the consumer if it is deployed systematically by integrating the social dimension of consumer perception and expectation prior to the smart meter rollout deployment. The cost-benefit analysis of the smart meter can provide a high potential consumer group depending on the smart meter feature specification. In Germany, the smart meter rollout is implemented in a positive, cost-effective area and for specific consumer groups. Social gaps can be addressed during the early pilot state where the barriers can be foreseen for future deployment.

7.4 Consumer behavior change invention

The consumer in the smart grid can be divided into three groups which are 1) the traditional consumer - who only uses electricity, 2) the proactive consumer - who is willing to reduce electricity consumption, and 3) prosumer - who can generate electricity and consume electricity. The number of prosumers in Thailand is still low due to the fact it is an early state of smart meter deployment. However, it is expected to increase when regulations are in place. The traditional consumer is mainly concerned about their living cost, which is directly correlated with daily energy expenditures. The lack of energy efficiency awareness provokes the traditional consumer to request lower energy prices from the government rather than adjust their energy consumption behavior.

The traditional consumer can become the proactive consumer through education and information flow. Providing real-time energy consumption data through an energy portal or an in-home display (IHD) activates consumer behavior change rather than receiving an electricity bill once a month. A smart meter without a data access channel only benefits the utility while the consumer is still in doubt about his electricity consumption. Real-time data and feedback are expected to boost consumer behavior change throughout a learning process.

7.4.1 Information flow experiment

As mentioned earlier, the smart meter is a two-way communication device which provides real-time data. The experiment of consumer behavior change through real-time information flow can accelerate smart meter deployment in the future. Unfortunately, there is no smart meter deployment in Thailand yet. It is very challenging to monitor consumer behavior without the smart meter. For the purpose of this research, a simple electricity consumption monitoring device was developed in cooperation with Keen Signal Co., Ltd. and was tested in Bangkok, Thailand (Keen Signal, 2018) (Figure 7.2). The experiment's results can address the research question of "How real-time and information feedback can provide knowledge for consumer behavior change invention," which is explained below.

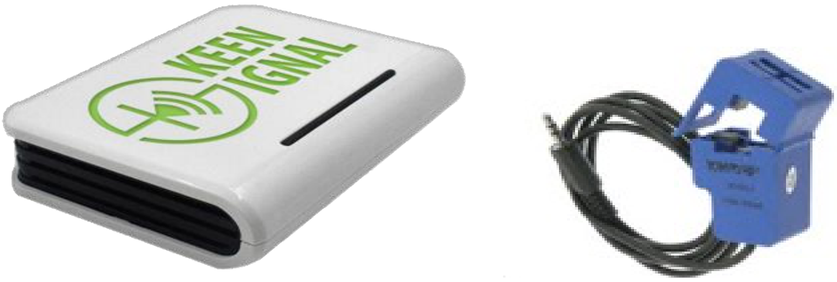


Figure 7.2 Monitoring device

The monitoring devices are installed in six houses due to budget limitations. The participants are divided into two equal groups, which are 1) the control group - without real-time data, and 2) the experimental group - with real-time data. The experiment group was not able to access their real-time data regarding the energy consumption baseline collection for the first three months. Then, they were offered the ability to access real-time data through the web portal (Figure 7.3).

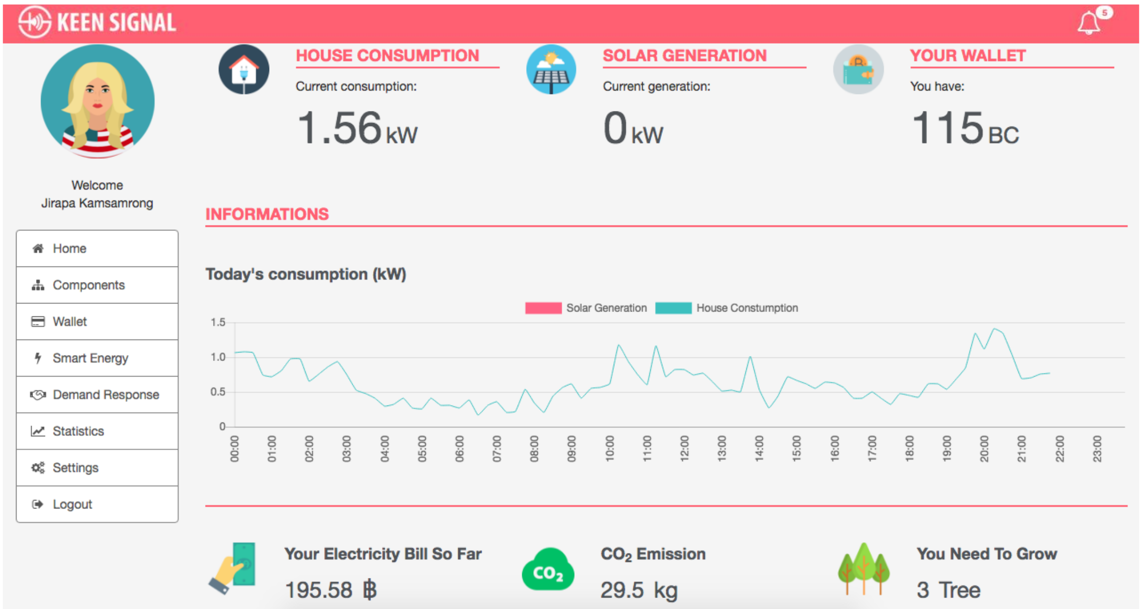


Figure 7.3 User interface of Keen Signal monitoring device

7.4.2 Consumer behavior with the information flow

The first impression of the experimental group is the historical electricity consumption data in daily, weekly, and monthly views, which provide electricity consumption behavior. It should be remarked that the participants are aware of the number difference in their electricity usage between the electric meter and the monitoring device from this research. The second impression is the environmental impact of their electricity consumption, which is presented in the number of trees needed to compensate for the CO_2 emissions.

One participant in the experimental group used real-time data and compared it with the daily historical profile to investigate the reason for high electricity consumption in a specific hour. The great advantage of the information flow and feedback can activate the learning process and behavior change. From the consumer behavior experiment, it was found that the participants did not try to reduce electricity consumption because of a lack of interest and incentive. Future research should be carried out on how resident consumer's behavior change is associated with price level signals with government support as the pilot project.

All participants in the experimental group expressed privacy concerns after they learned of the daily electricity consumption profile. In other words, a third party can obtain the data whether or not the occupants are at home. If no knowledge and regulatory support are provided, these privacy concerns may prevent smart meter deployment. The government should develop data protection regulations and provide information on the smart meter advantages to consumers prior to the rollout deployment.

Moreover, the experiment on the demand response (DR) program can be tested in future research by using the Keen Signal monitoring device when the smart meter is not yet in place. The large-scale DR pilot project can obtain consumer behavior with different backgrounds and price signals under the real DR deployment.

7.5 Dynamic pricing mechanism design for proactive consumers

The demand response (DR) program triggers the new dynamic pricing scheme in Thailand. The DR program was proposed by the Ministry of Energy but needs two electricity retailers for action. The voluntary DR program was tested within the industrial sector because of its higher energy consumption and the readiness of the automatic meter reader (AMR). The participants were notified with the date and incentive in advance, but the peak demand reduction was not effective because of the low number of participants and the unattractive incentive. The new pricing mechanism is the key success factor for the DR deployment especially in commercial and industrial sectors where critical peak pricing can be applied as an additional payment in an emergency situation.

Implementing the DR in the residential sector requires the smart meter for real-time monitoring. Currently, there are only two pricing schemes for the residential sector, which are the progressive rate and TOU. The rebate time pricing scheme (RTP) is considered as a potential pricing mechanism in the residential sector by providing a reward while the critical peak pricing can guarantee the reduction of the peak. An intensive pilot project on a new energy pricing mechanism can test the responsiveness of the consumer on dynamic pricing signals. The initiative on the dynamic electricity price development under the DR program is a step towards the liberalization of the electricity market.

7.6 Conclusion

Technology is a key player in providing smart energy service to consumers while consumer awareness and acceptance can increase technology adoption. Introducing new technology without background information and the perception of the consumer may lead to uncertainty in technology adoption. Many studies indicate that emerging technology deployments have failed due to the lack of proper social dimension integration.

Increasing energy efficiency awareness by using the technology advantage is one of the most important key drivers for consumer behavior change. Information flow and feedback should be provided to the consumer through the appropriate communication channels to encourage their behavior learning process. Providing energy consumption data in monetary terms rather than in the energy unit (kWh) is considered as a strong message, especially for the typical consumer who does not have an engineering background. The forecasted energy bill expenses through the user interface of the smart meter can help the consumer manage their electricity consumption within their budget through a notification. In addition, the distribution system operator (DSO) can create new energy services from the smart meter to the end-user.

The demand response (DR) program is a well-known energy efficiency invention for consumer behavior change and new dynamic pricing developments. The voluntary agreement does not guarantee a peak load reduction. Instead, the dynamic electricity pricing mechanism can play a vital role in behavior change. The responsive price should be addressed during the pilot state regarding individual consumer background preference. The commitment to cutting peak demand will help the electric utility for future power system planning, especially for the reserved power plant during the on-peak period. The DR pilot project is essential for pricing mechanism designs and testing the price responsiveness performance with different price levels and consumer groups.

The current status of the Thai electricity market limits smart grid development. The liberalization of the electricity market can enhance consumer behavior change with dynamic pricing regarding the energy supply and demand. The unbundled system would allow transparency in the electricity market. Electricity market reform is very challenging for Thailand, especially with the law and regulatory amendment which requires strong support from the government and electricity provider, and the consumer’s the readiness for the liberalization of the electricity market in Thailand.

Chapter 8

Summary and Policy Recommendation

8.1 Introduction

The smart grid enables the consumer in the traditional electricity system to become a proactive consumer and a prosumer. The smart grid roadmap in Thailand is focusing on improving the existing electricity grid to become a smart grid by integrating information and communication technology (ICT). The early state of smart grid deployment in Thailand overlooked the potential of the residential sector where the residential building can perform as a power plant and provide energy services to the smart grid by integrating the energy design concept of houses with potential technology packages.

This research aims to investigate and address the integrated-technology potential applications for the detached single-family building in Thailand to enhance the residential sector in smart grid development. Energy performance is assessed and compared between a reference building and an alternative building with integrated technology packages, including energy efficiency measures (EEM), a PV system, and an energy storage system application (Chapter 4). The high PV integration in the low voltage (LV) network is investigated to address the power quality impact and the PV hosting capacity. The active voltage control measures are proposed to allow a more distributed PV system in the network (Chapter 5). An economic assessment for the various building technology options, based on the total cost basis, is evaluated by considering the building's lifetime (Chapter 6). The current status of consumer behavior and perception toward smart grid development are assessed to identify the technical and non-technical barriers to becoming a smart user in the smart grid context (Chapter 7).

The summary is divided into three aspects as follows: technology, economic, and consumer behavior.

8.2 Technology aspect summary

The technology aspect is categorized into 1) a building simulation with the integrated technology packages, and 2) the power quality impact from the PV integration in the LV network.

8.2.1 Integrated technology in the building

The detached single-family house is the major building type in the residential sector of Thailand, which does not have a building energy standard or enforcement. As a result, the typical detached single-family building is built according to the individual user's requirements or depends on the real estate company. The reference building of the detached single-family house does not integrate any energy concept design features to reduce energy consumption in the building. The energy performance assessment of possible integrated technology options are summarized below.

- The integration of energy efficiency measures (EEM) such as insulation, double glazing windows, and external shading are essential for energy design in the building. It can reduce electricity consumption by 36% compared to the reference building.

- Deploying the EEM in the nearly zero energy building (nZEB in the Grid scenario) requires 27% less electricity from the grid than the reference building with only a PV system on the roof (REF in the GridPV scenario).
- The 14 kWh of battery energy storage (BES) system can increase the PV direct use by 163% compared to the reference building with a PV system but without a BES. However, the building with PV and battery energy storage systems needs to import electricity from the grid of 75 kWh/(m^2a).
- The combination of the energy efficiency measures, PV system and ice thermal energy storage (ITES) system offers the most advanced energy concept design in the building by storing the energy from the PV system during the day and providing the required cooling energy to the building at night. The amount of imported electricity is 60% lower than for the battery energy storage option.
- The detached single-family building with energy efficiency measures, PV, and ice thermal energy storage system integration can achieve an EnergyPLUS standard.

8.2.2 The power quality impact from PV integration in the low voltage network

The anxiety of high PV integration in the low voltage (LV) network has heightened power quality concerns to the distribution system operator. The current grid code is restricting the PV penetration of up to 15% of the distribution transformer (DTR) capacity. The key research findings are shown below.

- The distributed PV system can definitely integrate into the low voltage network by more than 15%. Limits of up to 75% of the distribution transformer without power quality concerns are suggested. However, it should be monitored carefully if the PV systems are connected at the end of the feeder.
- Grid reinforcement is a passive approach to support high PV penetration in the LV network. The main disadvantage is that it is an expensive option which requires new infrastructure investments, which may prevent the distribution system operator (DSO) from allowing many distributed PV systems in the LV network.
- The active voltage control strategies allow PV prosumers to provide energy services to the LV network but it requires a grid code revision.
- The most modest active voltage control strategy that can be implemented in any location is operating the power factor of the PV system at 0.95 lagging/leading to provide reactive power support.
- The voltage-dependent reactive power approach offers the most flexible voltage control possibilities when the PV system is connected at the long feeder.
- The distributed battery energy system with a voltage-reactive power droop control strategy can smooth overall voltage levels and their fluctuation. The distributed battery energy storage system has the two-fold benefits of increasing the PV direct use and providing energy service to the LV network. These are two great advantages for supporting ancillary services to the smart grid.

8.3 Economic aspect summary

The technology assessment has proved that the integration of the energy efficiency measures, PV system, and the ice thermal energy storage system is the most favorable package for the detached single-family house in Thailand. The economic assessment takes the technology potential into account for the total cost analysis including the carbon dioxide emission costs. The key findings from the economic assessment are:

- The energy cost accounts for 70% of the total cost considering the building's lifetime of 50 years.
- The integration of the energy efficiency measures, PV system, and ice thermal energy storage system has a lifetime cost of 835 EUR/m^2, and the net present value of 31,160 EUR, which is considered as an economically advantageous investment (at a discount rate of 0.54%).
- The energy efficiency measures integration in the building has a 36% lower energy cost compared to the reference building, and 27% lower than the reference building with the PV system.
- The carbon dioxide emissions cost of the reference building is 80% higher than the building with the energy efficiency measures and ice thermal energy storage systems.
- The Thai consumer has a willingness to pay (WTP) for the energy efficiency measures of 132 EUR/m^2 in the detached single-family building, which is higher than the market price.
- The willingness to pay for fully integrated technology package with the energy efficiency measures, PV system, and the energy storage system in the detached single-family house is approximately 711 EUR/m^2, which is 58% higher than the reference building. The willingness to pay of the energy storage system is lower than the market price. The incentive support and the investment cost reduction of the energy storage system can attract Thai consumers' attention in the future.

8.4 Consumer aspect summary

This research also investigates consumer behavior and perception toward smart grid development in Thailand. The key findings are:

- The consumer can be divided into three groups in the smart grid context: 1) traditional consumer, 2) proactive consumer, and 3) the prosumer.
- The Thai consumer still lacks knowledge of the smart meter's advantage by having over expectations in helping the consumer reduce electricity consumption without consumer behavior change.
- The information flow experiment shows that real-time and historical data can activate consumer behavior change through the learning process.
- The real-time data has two aspects: providing information flow to the consumer, but also raising privacy concerns from the energy consumption profile.
- The energy consumption data in monetary terms (baht) is a strong message, rather than the energy unit (kWh), to increase consumer awareness for consumer behavior change.

8.5 Energy policy recommendations

The key findings from the technology, economic, and consumer assessments lead to some energy practice approaches for enhancing the residential sector in future smart grid development. The recommendations of new energy policy are addressed below.

8.5.1 Introducing energy and CO_2 labels for detached single-family houses

Currently, there is no energy standard nor energy label for the detached single-family building in Thailand. The housing development agency designs the single-family house by focusing on the design and minimizing the cost to attract the consumer. The energy design in the residential building is overlooked due to the absence of law enforcement of standards and labels. The energy standard and label should provide the necessary energy performance information and CO_2 emissions of the building to the consumer for conscious consumer decisions.

Implementing energy labeling in the detached single-family residential building is very challenging. A voluntary program can be an initial program with the collaboration of the real estate companies. Intensive further research is required to identify the energy saving options, the economic impact, the consumer preference, and market acceptance for deploying an energy label in Thailand. Technology implications for various energy efficiency measures in the building sector have already proven energy saving potential. Robust energy policy and strong collaboration between the government and the private sector are the key drivers for introducing an energy performance label in Thailand. Financial support can be provided through a low-interest loan from the bank to the consumer for buying a detached family house with an energy label.

8.5.2 Grid code revision for residential prosumers

The rooftop PV system has attracted the traditional consumer to become the prosumer. Currently, the Thai electricity utility limits the PV capacity in the low voltage system by using the transformer capacity. The conservative grid code is considered as the bottleneck for the PV prosumer in clean energy development. Technology implications for such energy storage and the active voltage control strategy can overcome the power quality concerns of high PV penetration in the LV network. Instead of limiting the PV capacity in the low voltage network, the distribution system operator should revise the grid code to allow more distributed PV prosumers into the electricity network.

The distribution system operator should pay attention to power quality monitoring at low PV penetration rates in the network to foresee power quality challenges, which can be used to design appropriate active measures for high PV penetration in the future. The PV prosumer who causes the power quality problem must provide either the technical ancillary service or the service charge. The service charge can be in the form of a wheeling charge or additional reactive power called VAR charge. The surcharges can be neglected in case the prosumer can provide the reactive power service in an emergency. In other words, the prosumer receives the incentive for providing energy service to the network. The new energy policy invention for the PV prosumer can be done by integrating the dynamic wheeling charge in the net billing program where it reflects the real system cost from the PV system integration.

8.5.3 Smart meter rollout deployment

The smart meter rollout deployment would benefit both end-user and the distribution system operator if it is deployed systematically by taking background consumer knowledge and perception into account. Providing information knowledge of the smart meter's advantages can prevent uncertain deployment, such as with the privacy concerns. The smart meter rollout can be deployed where it is cost-effective rather than at every location. It should be remarked that the smart meter rollout investment is from the end user tax, and therefore it should be invested in the technology option or additional features that provide the maximum benefit to the end user. The distribution system operator should provide the data access channels to the consumer (if they are required) which can activate the proactive consumer transition through information flow.

8.5.4 Demand response (DR) with dynamic electricity price

The demand response (DR) program cannot be deployed in the residential sector due to the absence of a real-time monitoring device. The demand response program offers the dynamic electricity price scheme to the participant. However, each person has their own preference and responsiveness to price signals. The peak time rebate (PTR) scheme can be implemented in the residential sector where the consumer does not feel like they are being forced, but rather feel like they are being rewarded for good behavior. However, the peak time rebate cannot guarantee the peak load reduction compared to the critical peak pricing (CPP), which is more appropriate to implement in the commercial and industrial sectors. It should be noted that high-income consumers might not be interested in the demand response program because of the financial affordability of the high electricity price during on-peak.

A demand response pilot project in the residential sector by testing the pricing schemes and the levels can help the government design an appropriate incentive for the real DR deployment in the future. The initiative of the dynamic pricing scheme can be the first step of the liberalization of electricity market reform in Thailand.

8.5.5 Institutional arrangement and electricity market reform

The Ministry of Energy designs energy policy and renewable energy targets while the metropolitan electricity authority (MEA) and provincial electricity authority (PEA) are the only two distribution system operators in Thailand under the Ministry of Interior which enforce and design the grid code. Institutional rearrangement is not required for smart grid development if there is a strong collaboration toward clean energy system development.

Although the current electricity market is not the barrier for smart grid development, the unbundled electricity market system can be introduced to increase the transparency and competitiveness to all players in the electricity market. The Energy Regulatory Commission (ERC) of Thailand can play a significant role in energy policy towards the electricity market reform, which requires law amendment and public acceptance.

- empty page -

Future Work

This research work has been mainly focused on the single-family house with different energy design concepts. There are some interesting research aspects for future research that can be derived from this study, as follows.

District cooling with the ice thermal energy storage system

Future work would point out district cooling with the ice thermal energy storage application to scale up technical potential in Chapter 4. Investigation of district cooling could be an interesting topic to assess the dispatching schedule of reserved power plants. Optimizing PV generation with the ice thermal energy storage system would reduce the capacity reserve at peak demand, as well as the overall electricity generation cost. The district cooling approach can be also applied in the commercial and industrial sectors. Further studies should investigate control strategies with different electricity tariffs for techno-economic optimization.

Cost-benefit analysis

Regarding the existing electricity tariffs in Thailand, there are only block rated and time of use schemes available. Cost-benefit analysis of ice thermal energy storage applications could also be further investigated and compared with different electricity tariffs for the end-user. In addition, this research in Chapter 6 only investigated the levelized cost of electricity by using a yearly energy planning tool; it is worth examining dynamic electricity prices derived from power plant dispatching by performing simulations in hourly or 15-min intervals. Investigating avoided costs of electricity generation capacity at peak demand and transmission/distribution loss can prove important to district cooling with the ice thermal energy storage for electricity utility.

Power quality assessment in power system

The performance of the PV inverter and harmonic emissions used in this research in Chapter 4 are obtained from the literature. Experiments with real data for voltage control strategies should be performed to confirm these theoretical findings. A simulation with real data is a time-consuming option which requires a research budget for data collection devices. Future research on a larger scale of PV systems connected in a low voltage system might extend the explanations of power quality impact at a medium voltage system. Simulation of the whole power system in Bangkok is certainly required to investigate critical feeders for high PV systems integration in the future.

Consumer behavior change experiment

Concerning the skeptical results of consumer behavior change experiments in Chapter 7 due to the lack of budget and time, it can also be improved by increasing the number of users with different pricing schemes. Future work on demand response experiments with a deeper analysis of information exchange using in-home display integration and pricing mechanisms could prove consumer behavior change potential in the residential sector. Behavior change experiments in energy consumption require the budget to monitor and investigate for a time frame, therefore support from the government or a relevant research organization is essential

- empty page -

Reference

[1] Agora (2015). Current and future cost of photovoltaics: Long term scenarios for market development, system prices and LCOE of utility-scale PV system. Agora Energiewende. Berlin, Germany

[2] Alam, M. J., Muttaqi, K. M., & Sutanto, D. (2013). Mitigation of Rooftop Solar PV Impacts and Evening Peak Support by Managing Available Capacity of Distributed Energy Storage Systems. *IEEE Transactions on Power Systems,28*(4), 3874-3884. doi:10.1109/tpwrs.2013.2259269

[3] Alexander, B. R. (2010). Dynamic Pricing? Not So Fast! A Residential Consumer Perspective. *The Electricity Journal,23*(6), 39-49. doi:10.1016/j.tej.2010.05.014

[4] Apichatsiritham, N., Wattanasakornkul, A., Siriboonrod, P., & Kritprachan, P. (2015). Increasing the PV hosting capacity in the LV network. *2015 PEA Conference.* Bangkok, Thailand.

[5] Arteconi, A., Hewitt, N., & Polonara, F. (2013). Domestic demand-side management (DSM): Role of heat pumps and thermal energy storage (TES) systems. *Applied Thermal Engineering,51*(1-2), 155-165. doi:10.1016/j.applthermaleng.2012.09.023

[6] Audibert, M., He, Y., Mathonnat, J. (2013) Multinomial and Mixed Logit Modeling in the Presence of Heterogeneity: A Two-Period Comparison of Healthcare Provider Choice in Rural China.

[7] Bariss, U., Timma, L., & Blumberga, D. (2014). Smart Metering Pilot Project Results. *Energy Procedia,61*, 2176-2179. doi:10.1016/j.egypro.2014.12.103

[8] Becchio, C., Bottero, M., Corgnati, S., & Ghiglione, C. (2015). NZEB Design: Challenging between Energy and Economic Targets. *Energy Procedia,78*, 2070-2075. doi:10.1016/j.egypro.2015.11.226

[9] Biebaut, J. E. (2017). Nearly zero energy buildings: an economic analysis. Faculty of economics and business administration. Ghent University

[10] Bishop, J. D., Axon, C. J., Bonilla, D., Tran, M., Banister, D., & Mcculloch, M. D. (2013). Evaluating the impact of V2G services on the degradation of batteries in PHEV and EV. *Applied Energy,111*, 206-218. doi:10.1016/j.apenergy.2013.04.094

[11] Blumsack, S., & Fernandez, A. (2012). Ready or not, here comes the smart grid! *Energy,37*(1), 61-68. doi:10.1016/j.energy.2011.07.054

[12] BMU (2018). Climate Action in Figures: Facts, Trends and Incentives for German Climate Policy 2018 edition. Federal Ministry for Environment, Nature Conservation and Nuclear Safety (BMU). Germany

[13] BMWi (2017). Renewable Energy Sources in Figures: National and International Development, 2017. Federal Ministry for Economic Affairs and Energy. Germany

[14] BMWi (2018). Sixth “Energy Transition” Monitoring Report, The Energy of the Future: Reporting Year 2016-Summary. Germany

[15] BMWi (2019). Zahlen und Fakten Energiedaten. Germany

[16] BOT (2018). Historical inflation rate and interest rate. Bank of Thailand. Bangkok, Thailand

[17] BPIE (2013). Implementing the cost-optimal: Methodology in EU countries, lessons learned from three cases studies. Buildings Performance Institute Europe. Brussels. Belgium

[18] BPIE (2015). Discount rats in energy system analysis: Discussion paper. Buildings Performance Institute Europe. Brussels. Belgium

[19] Breidert, C., Hahsler, M., & Reutterer, T. (2006). A Review of Method for Measuring Willingness-to-Pay. Innovation Marketing.

[20] Carroll, J., Lyons, S., & Denny, E. (2014). Reducing household electricity demand through smart metering: The role of improved information about energy saving. *Energy Economics,45*, 234-243. doi:10.1016/j.eneco.2014.07.007

[21] CEN-CENELEC-ETSI (2012). Smart Grid Coordination Group. Smart Grid Reference Architecture; Technical Report; CEN-CENELEC-ETSI: Brussels, Belgium, 2012

[22] Chaichana, C., Charters, W. W., & Aye, L. (2001). An ice thermal storage computer model. *Applied Thermal Engineering,21*(17), 1769-1778. doi:10.1016/s1359-4311(01)00046-1

[23] Chau, C., Tse, M., & Chung, K. (2010). A choice experiment to estimate the effect of green experience on preferences and willingness-to-pay for green building attributes. *Building and Environment,45*(11), 2553-2561. doi:10.1016/j.buildenv.2010.05.017

[24] Colak, I., Bayindir, R., Fulli, G., Tekin, I., Demirtas, K., & Covrig, C. (2014). Smart grid opportunities and applications in Turkey. *Renewable and Sustainable Energy Reviews,33*, 344-352. doi:10.1016/j.rser.2014.02.009

[25] Connor, P. M., Baker, P. E., Xenias, D., Balta-Ozkan, N., Axon, C. J., & Cipcigan, L. (2014). Policy and regulation for smart grids in the United Kingdom. Renewable and Sustainable Energy Reviews,40, 269-286. doi:10.1016/j.rser.2014.07.065

[26] Crispim, J., Braz, J., Castro, R., & Esteves, J. (2014). Smart Grids in the EU with smart regulation: Experiences from the UK, Italy and Portugal. *Utilities Policy,31*, 85-93. doi:10.1016/j.jup.2014.09.006

[27] CRS (2018). The Smart Grid: Status and Outlook. Congressional Research Service.

[28] CSE (2018). Smart meter. Center for sustainable Energy. London, UK.

[29] DEDE (2009). Air conditioning system. Department of Alternative Energy Development and Efficiency. Bangkok, Thailand

[30] DEDE (2017). Energy Statistic of Thailand. Department of Alternative Energy Development and Efficiency. Ministry of Energy of Thailand, Bangkok, Thailand

[31] Demirok, E., Sera, D., Teodorescu, R., Rodriguez, P., & Borup, U. (2009). Clustered PV inverters in LV networks: An overview of impacts and comparison of voltage control strategies. *2009 IEEE Electrical Power & Energy Conference (EPEC)*. doi:10.1109/epec.2009.5420366

[32] DGNB (2012) Criterion ENV2.1: Life Cycle Assessment. German Sustainable Building Council. Germany

[33] DIgSILENT (2017). Technical Reference Documentation: Static Genertor. DIgSILIET GmBH.

[34] Döbelt, S., Jung, M., Busch, M., & Tscheligi, M. (2015). Consumers' privacy concerns and implications for a privacy preserving Smart Grid architecture—Results of an Austrian study. *Energy Research & Social Science,9*, 137-145. doi:10.1016/j.erss.2015.08.022

[35] Dufo-López, R., & Bernal-Agustín, J. L. (2015). A comparative assessment of net metering and net billing policies. Study cases for Spain. *Energy,84*, 684-694. doi:10.1016/j.energy.2015.03.031

[36] Ebad, M., & Grady, W. M. (2016). An approach for assessing high-penetration PV impact on distribution feeders. *Electric Power Systems Research,133*, 347-354. doi:10.1016/j.epsr.2015.12.026

[37] EC (2011). Smart Grids: from innovation to deployment. Brussel, European Commission.

[38] EC (2012). European task force for the implementation of smart grids into the European internal market: Mission and Work Programme. Brussel, European Commission.

[39] EC (2015a). Best practices on Renewable Energy Self-consumption. Brussel, European Commission.

[40] EC (2015b). Smart Electricity Grids and Meters in the EU Member States. Brussel, European Commission.

[41] ECOFY (2011). Primary Energy Factors for Electricity in Buildings: Toward a flexible electricity supply. Netherland.

[42] EEG (2012) *Erneuerbare-Energien-Geset.* Gesetz für den Vorrang Erneuerbarer Energien. Budesministerium des Justiz und für Verbraucherschutz

[43] EEG (2017) *Erneuerbare-Energien-Geset. Gesetz* für Ausbau erneuerbarer Energien. Budesministerium des Justiz und für Verbraucherschutz

[44] EGAT (2013). EGAT Smart Grid Development Roadmap between 2013-2032. Electricity Generating Authority of Thailand. Bangkok, Thailand.

[45] EGAT (2017a). Energy label number 5 for AC system. Electricity Generating Authority of Thailand. Bangkok, Thailand.

[46] EGAT (2017b). Capital cost of electricity in Thailand and retail electricity price components. PowerPoint presentation. Nonthaburi, Thailand

[47] EGS (2016). Preksa Energy Plus House. Bangkok, Thailand.

[48] EIA (2011). Smart grid legislative regulatory policy and case studies. U.S. Energy Information Administration. USA.

[49] EIA (2018). Levelized cost and levelized avoided cost of new generation resource in the annual energy outlook 2018. Energy Information Administration. U.S. Department of Energy. Washington, USA

[50] Eisen-Hecht, Jonathan I. & Kramer, Randall A. & Huber, Joel, 2004. "A Hierarchical Bayes Approach To Modeling Choice Data: A Study Of Wetland Restoration Programs," 2004 Annual meeting, August 1-4, Denver, CO 20253, American Agricultural Economics Association

[51] EPPO (2000). Electricity supply industry reform and Thailand power pool. Energy Policy and Planning Office. Ministry of Energy, Bangkok, Thailand

[52] EPPO (2009). Load research of Thailand. Energy Policy and Planning Office. Bangkok, Thailand

[53] EPPO (2015). Feed in Tariff in Thailand 2015. Energy Policy and Planning Office. Ministry of Energy of Thailand, Bangkok, Thailand

[54] EPPO (2017a). Energy Statistic of Thailand. Energy Policy and Planning Office. Ministry of Energy of Thailand, Bangkok, Thailand

[55] EPPO (2017b). SPP Hybrid Firm and VSPP Semi Firm Feed in Tariff. Energy Policy and Planning Office. Ministry of Energy of Thailand, Bangkok, Thailand

[56] EPRI (2012), *A Case Study on the Demonstration of Storage for Simultaneous Voltage Smoothing and Peak Shifting. Electric Power Research Institute.* Palo Alto, CA

[57] ERC (2014). Feed in Tariff in 2014. Energy Regulatory Commission. Bangkok, Thailand

[58] ERC (2009). Adder rate (feed-in premium) for renewable energy in Thailand. Energy Regulatory Commission. Bangkok, Thailand

[59] ERC (2017). Information of retail electricity price of Thailand in 2017.

[60] Faruqui, A., Harris, D., & Hledik, R. (2010). Unlocking the €53 billion savings from smart meters in the EU: How increasing the adoption of dynamic tariffs could make or break the EU's smart grid investment. *Energy Policy,38*(10), 6222-6231. doi:10.1016/j.enpol.2010.06.010

[61] Fattori, F., Anglani, N., & Muliere, G. (2014). Combining photovoltaic energy with electric vehicles, smart charging and vehicle-to-grid. *Solar Energy,110*, 438-451. doi:10.1016/j.solener.2014.09.034

[62] Fekete, K., Klaic, Z., & Majdandzic, L. (2012). Expansion of the residential photovoltaic systems and its harmonic impact on the distribution grid. *Renewable Energy,43*, 140-148. doi:10.1016/j.renene.2011.11.026

[63] Fisch M. Norbert, Willken, T., & Stähr, C. (2013). Energy PLUS: Buildings and districts as renewable energy source. Germany

[64] Fraunhofer ISE (2017). Energy Charts. https://www.energy-charts.de/index_de.htm

[65] Fraunhofer ISE (2019). Recent Facts about Photovoltaics in Germany.

[66] Galassi, V., & Madlener, R. (2017). The Role of Environmental Concern and Comfort Expectations in Energy Retrofit Decisions. *Ecological Economics,141*, 53-65. doi:10.1016/j.ecolecon.2017.05.021

[67] GIZ (2017). Analysis of Indian Electricity Distribution Systems for the Integration of High Shares of Rooftop PV: Final Report. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmBH.

[68] Goulden, M., Bedwell, B., Rennick-Egglestone, S., Rodden, T., & Spence, A. (2014). Smart grids, smart users? The role of the user in demand side management. *Energy Research & Social Science,2*, 21-29. doi:10.1016/j.erss.2014.04.008

[69] Greacen, S. C., & Greacen, C. (2004). Thailand's electricity reforms: privatization of benefits and socialization of costs and risks. *Pacific Affairs, 77*(3), 517-541.

[70] Hargreaves, T., Nye, M., & Burgess, J. (2013). Keeping energy visible? Exploring how householders interact with feedback from smart energy monitors in the longer term. *Energy Policy,52*, 126-134. doi:10.1016/j.enpol.2012.03.027

[71] Heaps, C.G. (2016). *Long-range Energy Alternatives Planning (LEAP) system.*[Software version: 2018.1.20] Stockholm Environment Institute. Somerville, MA, USA. https://www.energycommunity.org

[72] Hill, C. A., Such, M. C., Chen, D., Gonzalez, J., & Grady, W. M. (2012). Battery Energy Storage for Enabling Integration of Distributed Solar Power Generation. *IEEE Transactions on Smart Grid,3*(2), 850-857. doi:10.1109/tsg.2012.2190113

[73] IEA (2011). Smart Grid-Smart Customer Policy Needs. International Energy Agency. Paris

[74] IEA (2014a). The power of transformation: wind, sun, and the economics of flexible power system. International Energy Agency. Paris.

[75] IEA (2014b). Technology Roadmap Energy Storage. International Energy Agency. Paris

[76] IEA (2017a). Southeast Asia Energy Outlook 2017. International Energy Agency. Paris

[77] IEA (2017b). Energy Technology Perspectives (ETP Model 2017). International Energy Agency. Paris, France

[78] IEEE (1992). IEEE 519-1992 Recommended Practices and Requirement for Harmonic Control in Electrical Systems.

[79] IEI (2017). Electric Company Smart Meter Deployment: Foundation for a Smart Grid. The Edison Foundation. Institute for Electric Innovation. Washington DC. USA

[80] Ihm, P., Krarti, M., & Henze, G. P. (2004). Development of a thermal energy storage model for EnergyPlus. *Energy and Buildings,36*(8), 807-814. doi:10.1016/j.enbuild.2004.01.021

[81] IISD (2013). Incentive for Renewable Energy in Southeast Asia: Case study of Thailand. International Institute for Sustainable Development. Canada

[82] Iqbal, M. I., Himmler, R., & Gheewala, S. H. (2017). Potential life cycle energy savings through a transition from typical to energy plus households: A case study from Thailand. *Energy and Buildings,134*, 295-305. doi:10.1016/j.enbuild.2016.11.002

[83] IRENA (2015). Battery storage for renewables market status and technology outlook. International Renewable Energy Agency

[84] IRENA (2017). Electricity storage and renewables: costs and markets to 2030. International Renewable Energy Agency. Abu Dhabi, United Arab Emirates

[85] Jareemit, D. (2015). Uncertainty Distribution of Air Infiltration Rates of Thai Detached Homes for Energy Model. *Journal of Architectural/Planning Research and Studies (JARS), 12(2),* 39-52.

[86] JASE-W (2015). Thermal Energy Storage Air Conditioning System. Heat Pump and Thermal Storage Center of Japan. Japanese Business Alliance for Smart Energy Worldwide. Japan

[87] Jirapornanan A. (2010), Study of smart grid for Thailand and identification of the required research and development. *PICMET 2010 Technology Management for Global Economic Growth.*

[88] JRC (2011). Smart Grid Projects in Europe: Lessons learned and current developments. Joint Research Center. Netherlands

[89] JRC (2017). Smart grid projects outlook 2017: Facts, figures and trends in Europe. Joint Research Centre. Netherland

[90] Kamsamrong, J., & Sorapipatana, C. (2014). An assessment of energy security in Thailand's power generation. *Sustainable Energy Technologies and Assessments,7*, 45-54. doi:10.1016/j.seta.2014.03.003

[91] Kaufmann, S., Künzel, K., & Loock, M. (2013). Customer value of smart metering: Explorative evidence from a choice-based conjoint study in Switzerland. *Energy Policy,53*, 229-239. doi:10.1016/j.enpol.2012.10.072

[92] Keen Signal (2018). Home energy monitoring with user interface. Bangkok, Thailand

[93] Kempton, W., & Tomić, J. (2005). Vehicle-to-grid power fundamentals: Calculating capacity and net revenue. *Journal of Power Sources,144*(1), 268-279. doi:10.1016/j.jpowsour.2004.12.025

[94] Klein, S.A. et al. (2017). TRNSYS 18: A Transient System Simulation Program, Solar Energy Laboratory, University of Wisconsin, Madison, USA

[95] Kloza, D., Dijk, N. V., & Hert, P. D. (2015). Assessing the European Approach to Privacy and Data Protection in Smart Grids. Lessons for Emerging Technologies. *Smart Grid Security,*11-47. doi:10.1016/b978-0-12-802122-4.00002-x

[96] Krarti, M. (2000). Energy Audit of Building Systems: An Engineering Approach. Taylor&Francis Group. New York, USA.

[97] Krishnamurti, T., Schwartz, D., Davis, A., Fischhoff, B., Bruin, W. B., Lave, L., & Wang, J. (2012). Preparing for smart grid technologies: A behavioral decision research approach to understanding consumer expectations about smart meters. *Energy Policy,41*, 790-797. doi:10.1016/j.enpol.2011.11.047

[98] Kumanayake, R., & Luo, H. (2018). A tool for assessing life cycle CO_2 emissions of buildings in Sri Lanka. *Building and Environment,128*, 272-286. doi:10.1016/j.buildenv.2017.11.042

[99] Kurnitski, J. (2011). How to calculate cost optimal nZEB energy performance. REHVA Journal, 36-41

[100] Lamedica, R., Teodori, S., Carbone, G., & Santini, E. (2015). An energy management software for smart buildings with V2G and BESS. *Sustainable Cities and Society,19*, 173-183. doi:10.1016/j.scs.2015.08.003

[101] Langaard, J. H. (2016). Voltage Support Strategies for Overvoltage Prevention of Distributed Solar Inverters in Low-Voltage Networks. Norwegian University of Science and Technology.

[102] Levine S., W. (1999). Control System Applications. Taylor&Francis Group.

[103] Liu, X., Aichhorn, A., Liu, L., & Li, H. (2012). Coordinated Control of Distributed Energy Storage System With Tap Changer Transformers for Voltage Rise Mitigation Under High Photovoltaic Penetration. *IEEE Transactions on Smart Grid,3*(2), 897-906. doi:10.1109/tsg.2011.2177501

[104] López, M., Torre, S. D., Martín, S., & Aguado, J. (2015). Demand-side management in smart grid operation considering electric vehicles load shifting and vehicle-to-grid support. *International Journal of Electrical Power & Energy Systems,64*, 689-698. doi:10.1016/j.ijepes.2014.07.065

[105] Louviere, J. J., Flynn, T. N., & Carson, R. T. (2010). Discrete Choice Experiments Are Not Conjoint Analysis. *Journal of Choice Modelling,3*(3), 57-72. doi:10.1016/s1755-5345(13)70014-9

[106] Luthander, R., Widén, J., Nilsson, D., & Palm, J. (2015). Photovoltaic self-consumption in buildings: A review. *Applied Energy,142*, 80-94. doi:10.1016/j.apenergy.2014.12.028

[107] Maccraken, M. (2003). Thermal Energy Storage Myths. ASHEAE Journal. 36-42

[108] Mah, D. N., Vleuten, J. M., Hills, P., & Tao, J. (2012). Consumer perceptions of smart grid development: Results of a Hong Kong survey and policy implications. *Energy Policy,49*, 204-216. doi:10.1016/j.enpol.2012.05.055

[109] Mangham, L. J., Hanson, K., & Mcpake, B. (2008). How to do (or not to do) … Designing a discrete choice experiment for application in a low-income country. Health Policy and Planning, 24(2), 151–158. doi: 10.1093/heapol/czn047

[110] MDPI (2016). Economics of Residential Photovoltaic Battery Systems in Germany: The casr of Tesla's Powerwall. Basel, Switzerland

[111] MEA (2012). MEA Smart Grid Roadmap between 2012-2051. Metropolitan Electricity Authority. Bangkok, Thailand.

[112] MEA (2016). Requirement for LV network connection. Metropolitan Electricity Authority (MEA).

[113] MECON (2014). Effective energy efficiency policy implementation targeting "New Modern Energy Consumer" in the Greather Mekong Sub-region. Bangkok, Thailand.

[114] Meteonorm (2016). Weather and irradiation data. Metrotest AG. Switzerland.

[115] Min, J. (2014). Energy Efficient Lighting: Consumer Preference, Choices, and System Side Effects. Carnegie Mellon University.

[116] MOE (2013). National Smart Grid Roadmap of Thailand (2013-2036). Ministry of Energy. Energy Policy and Planning Office (EPPO). Bangkok, Thailand

[117] MOE (2015a). Thailand Integrated Energy Blueprint (TIEB) (2015-2036). Ministry of Energy, Bangkok, Thailand

[118] MOE (2015b). The Alternative Energy Development Plan (AEDP) (2015-2036). Ministry of Energy, Bangkok, Thailand

[119] MOE (2015c). The Energy Efficiency Plan (EEP) (2015-2036). Ministry of Energy, Bangkok, Thailand

[120] MOE (2015d). The Power Development Plan 2015 (2015-2036). Ministry of Energy, Bangkok, Thailand

[121] Naguib, R. (2006). Hybrid Ice Thermal Energy Storage: All-in-one Innovative New System Concept. Air Conditioning and Refrigeration Journal. 101-106

[122] Naus, J., Spaargaren, G., Vliet, B. J., & Horst, H. M. (2014). Smart grids, information flows and emerging domestic energy practices. *Energy Policy,68*, 436-446. doi:10.1016/j.enpol.2014.01.038

[123] NIST (2012). Policy, Regulation and Implementation of Smart Grid in the US. National Institute of Standards and Technology. USA.

[124] NREL (2011). The cost of renewable energy spreadsheet tool (CREST). National Renewable Energy Laboratory. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. USA

[125] NREL (2014). State Energy Efficiency Resource Standards: Design, Status, and Impacts. National Renewable Energy Laboratory, U.S. Department of Energy Office of Energy Efficiency & Renewable Energy

[126] NREL (2015). Wheeling and Banking Strategies for Optimal Renewable Energy Deployment: International Experiences. National Renewable Energy Laboratory. U.S. Energy Information Administration. USA.

[127] NSO (2010). Private household in Thailand. National Statistical Office of Thailand. Ministry of Information and Communication Technology. Bangkok. Thailand

[128] NSO (2017). National Statistic: Economic and Population. National Statistical Office. Ministry of Information and Communication Technology. Bangkok. Thailand

[129] NSO, (2018). List of building construction statistical. National Statistical Office. Ministry of Information and Communication Technology. Bangkok. Thailand

[130] OECD.Stat (2018). Organization for Economic Co-Operation and Development (OECD) Statistic Data. https://stats.oecd.org/Index.aspx?DataSetCode=AIR_GHG

[131] Ofgem (2011). Energy Demand Research Project: Final analysis. UK.

[132] Pantziris, K. (2014). Voltage Support Strategies in a Rural Voltage Network with High Photovoltaic Penetration. Delft University of Technology.

[133] Patsalides, M., Stavrou, A., Efthymiou, V., & Georghiou, G. E. (2012). Towards the establishment of maximum PV generation limits due to power quality constraints. *International Journal of Electrical Power & Energy Systems,42*(1), 285-298. doi:10.1016/j.ijepes.2012.03.043

[134] PEA. (2015). PEA Smart Grid Roadmap Revision Aligned with National Policy between 2016-2036. Provincial Electricity Authority. Bangkok, Thailand.

[135] Phatidamrongkul, T.& Varodompun, J. (2012). Field Efficiency of Split-type Air Coniditoners with Evaporative-cooled Condenser. *Journal of Architectural/Planning Research and Studies (JARS), 9(1),* 101-112.

[136] Potter, C. W., Archambault, A., & Westrick, K. (2009). Building a smarter smart grid through better renewable energy information. *2009 IEEE/PES Power Systems Conference and Exposition*. doi:10.1109/psce.2009.4840110

[137] PPC (2016). Moma: Smart City Mannheim. Power Plus Communications. Germany

[138] Punyachai , R., Ongsakul, W., & Schmidt, U. Schmidt. (2014). Impact of high solar rooftop PV penetration on voltage profiles in distribution systems. *2014 International Conference and Utility Exhibition on Green Energy for Sustainable Development (ICUE)*. Pattaya, Thailand

[139] Rafi, F., Hossain, M., & Lu, J. (2016). Hierarchical controls selection based on PV penetrations for voltage rise mitigation in a LV distribution network. *International Journal of Electrical Power & Energy Systems,81*, 123-139. doi:10.1016/j.ijepes.2016.02.013

[140] Rechkwitz, A. (2002). Toward a Theory of Social Practices: A Development in Cluturalist Theorizing. *European Journal of Social Theory, 5*(2), 243-263.

[141] REIC (2018). Detached family house growth. Real Estate Information Center. Government Housing Bank. Bangkok, Thailand.

[142] Saksornchai, T., Siriwan, P., & Chumchawalit, S. (2015). Modeling of the Low Voltage Distribution System of PEA with PV Rooftop. *2015 PEA Conference.* Bangkok, Thailand.

[143] Sammer, K., & Wüstenhagen, R. (2006). The influence of eco-labelling on consumer behaviour – results of a discrete choice analysis for washing machines. *Business Strategy and the Environment,15*(3), 185-199. doi:10.1002/bse.522

[144] Sawtooth (2000). Hierarchical Bayes: Why all the attention?. Research Publishers LLC.

[145] Sawtooth (2010). Sample Size Issues for Conjoint Analysis. Research Publishers LLC.

[146] Schreiber, M., & Hochloff, P. (2013). Capacity-dependent tariffs and residential energy management for photovoltaic storage systems. *2013 IEEE Power & Energy Society General Meeting*. doi:10.1109/pesmg.2013.6672200

[147] Schultz, P. W., Estrada, M., Schmitt, J., Sokoloski, R., & Silva-Send, N. (2015). Using in-home displays to provide smart meter feedback about household electricity consumption: A randomized control trial comparing kilowatts, cost, and social norms. *Energy,90*, 351-358. doi:10.1016/j.energy.2015.06.130

[148] Sehar, F., Pipattanasomporn, M., & Rahman, S. (2016). An energy management model to study energy and peak power savings from PV and storage in demand responsive buildings. *Applied Energy,173*, 406-417. doi:10.1016/j.apenergy.2016.04.039

[149] SGIG (2007). Smart Grid Investment Grant Program. U.S. Department of Energy. USA

[150] Shivashankar, S., Mekhilef, S., Mokhlis, H., & Karimi, M. (2016). Mitigating methods of power fluctuation of photovoltaic (PV) sources – A review. *Renewable and Sustainable Energy Reviews,59*, 1170-1184. doi:10.1016/j.rser.2016.01.059

[151] Simmonds, P. (1993), Chilled water production: Storage Priority Control Strategy. Building Services Engineering Research and Technology, 14(2), 51-59.

[152] Sonnen (2018). Sonnen Edges into the Grid Services Market in Germany.

[153] Stetz, T., Marten, F., & Braun, M. (2013). Improved Low Voltage Grid-Integration of Photovoltaic Systems in Germany. *IEEE Transactions on Sustainable Energy,4*(2), 534-542. doi:10.1109/tste.2012.2198925

[154] STIEBEL (2016). Product Informatieblad (WPF). STIEBEL ELTRON. Thailand

[155] Surahman, U., Kubota, T., & Higashi, O. (2015). Life Cycle Assessment of Energy and CO_2 Emissions for Residential Buildings in Jakarta and Bandung, Indonesia. *Buildings,5*(4), 1131-1155. doi:10.3390/buildings5041131

[156] Tan, K. M., Ramachandaramurthy, V. K., & Yong, J. Y. (2016). Integration of electric vehicles in smart grid: A review on vehicle to grid technologies and optimization techniques. *Renewable and Sustainable Energy Reviews,53*, 720-732. doi:10.1016/j.rser.2015.09.012

[157] Taotong, S., & Tonprom, S. Fire protection approach for PV rooftop system. *2015 PEA Conference.* Bangkok, Thailand.

[158] TESLA (2017). Powerwall: Technical Specs. USA

[159] The World Bank (2017). Statistic by country. Retrieve from http://data.worldbank.org/indicator

[160] The World Bank (2019). Solar resource map of Thailand and Germany. Retrieve from https://solargis.com/maps-and-gis-data/download

[161] Tonkoski, R., Turcotte, D., & El-Fouly, T. H. (2012). Impact of High PV Penetration on Voltage Profiles in Residential Neighborhoods. *IEEE Transactions on Sustainable Energy,3*(3), 518-527. doi:10.1109/tste.2012.2191425

[162] Toobpae, P., & Sudta, P. (2015). Assessment of PV rooftop topology in the LV network. *PEA Conference Technology for Distribution System Development. 2015 PEA Conference*. Bangkok, Thailand.

[163] Torriti, J., Hassan, M. G., & Leach, M. (2010). Demand response experience in Europe: Policies, programmes and implementation. *Energy,35*(4), 1575-1583. doi:10.1016/j.energy.2009.05.021

[164] Train, K. (2002). Discrete Choice Methods with Simulation. University of California, Berkeley. National Economic Research Associates

[165] TRANE (2009). Ice storage and application. Trane Engineers Newsletter Live Series.

[166] TRNSYS (2006) Thermal Energy System Specialist. Transient System Simulation Tool. Wisconsin.

[167] UN (2015). Paris Agreement 2015. United Nation.

[168] VDE (2018). Generators connected to the low-voltage distribution network. VDE Verband der Elecktronik Informationstechnik e. V.

[169] Verbong, G. P., Beemsterboer, S., & Sengers, F. (2013). Smart grids or smart users? Involving users in developing a low carbon electricity economy. *Energy Policy,52*, 117-125. doi:10.1016/j.enpol.2012.05.003

[170] Wattana, S., Sharma, D., & Vaiyavuth, R. (2008). Electricity Industry Reforms in Thailand: A Historical Review. *GMSARN International Journal, 2*(2), 41-52.

[171] Watts, D., Valdés, M. F., Jara, D., & Watson, A. (2015). Potential residential PV development in Chile: The effect of Net Metering and Net Billing schemes for grid-connected PV systems. *Renewable and Sustainable Energy Reviews,41*, 1037-1051. doi:10.1016/j.rser.2014.07.201

[172] Wilby, M. R., González, A. B., & Díaz, J. J. (2014). Empirical and dynamic primary energy factors. *Energy,73*, 771-779. doi:10.1016/j.energy.2014.06.083

[173] Wisuttisak, P. (2010). Regulatory framework of Thai electricity sector, Australian school of business. The university of New South Wales, Sydney

[174] Witt, E., Lill, I., & Nuuter, T. (2015). Comparative Analysis of Current Guidance for the Evaluation of Building Retrofit Investments. *Procedia Economics and Finance,21*, 321-328. doi:10.1016/s2212-5671(15)00183-5

[175] Yuan, J., Shen, J., Pan, L., Zhao, C., & Kang, J. (2014). Smart grids in China. *Renewable and Sustainable Energy Reviews,37*, 896-906. doi:10.1016/j.rser.2014.05.051

[176] Zhang, Q., Tezuka, T., Ishihara, K. N., & Mclellan, B. C. (2012). Integration of PV power into future low-carbon smart electricity systems with EV and HP in Kansai Area, Japan. *Renewable Energy,44*, 99-108. doi:10.1016/j.renene.2012.01.00

- empty page -

Abbreviation

AC	Air conditioning
Adder	Feed in Premium or Adder Program
AEDP	Alternative Energy Development Plan
AMI	Advance Metering Infrastructure
AMR	Automatic Meter Reader
APEC	Asia Pacific Economic Cooperation
BAU	Business as Usual
BBL	Barrel
BEC	Building Energy Code
BES	Batter Energy System
BOT	Bank of Thailand
CBC	Choice Based Conjoint
CCGT	Combined Cycle Gas Turbine
CEN	Comité Européen de Normalisation
CENELEC	Comité Européen de Normalisation Electrotechnique
CO_2	Carbon Dioxide
COP	Coefficient of Performance
CPP	Critical Peak Pricing
CPUC	California Public Utilities Commission
DCE	Discrete Choice Experiment
DER	Distributed Energy Resource
DHW	Domestic Hot Water
DLR	Dynamic Line Ratings
DMS	Distribution Management System
DR	Demand Response
DSM	Demand Side Management
DSO	Distribution System Operator
DTR	Distribution Transformer

EC	European Commission
EEG	Erneuerbare-Energien-Gesetz
EEM	Energy Efficiency Measures
EEP	Energy Efficiency Plan
EERS	Energy Efficiency Resource Standard
EGAT	Electricity Generating Authority of Thailand
EMS	Energy Management System
EPPO	Energy Policy and Planning Office
EPRI	Electric Power Research Institute
ERC	Energy Regulatory Commission
ESS	Energy Storage System
ETSI	European Telecommunications Standard Institute
EU	European Union
EUR	Euro
EV	Electric Vehicle
FACTS	Flexible AC Transmission Systems
FCU	Fan Coil Unit
FiT	Feed in Tariff
Ft	Fuel Price Volatility Adjustment Tariff
G2V	Grid to Vehicle
GDP	Gross Domestic Product
GIS	Geographic Information Systems
Grid	Building without PV
GridPV	Building with PV System
GridPVBES	Building with PV System and Battery Energy Storage System
GridPVITES	Building with PV System and Ice Thermal Energy Storage System
GridRein	Grid Reinforcement
HB	Hierarchical Bayes
HEPs	High Energy Performance Standard
ICT	Information and Communication Technology
IEA	International Energy Agency

IHD	In Home Display
IPP	Independence Power Producer
IRENA	International Renewable Energy Agency
IRR	Internal Rate of Return
ITES	Ice Thermal Energy Storage
ktoe	Kilotonnes of Oil Equivalent
kW	Kilowatt
kWh	Kilowatt-Hour
LCOE	Levelized Cost of Electricity
LEAP	Long-range Energy Alternative Planning
LED	Light-Emitting Diode
LV	Low Voltage
MEA	Metropolitan Electricity Authority
MEPs	Minimum Energy Performance Standard
MMBTU	One Million British Thermal Unit
MOE	Ministry of Energy
MSW	Municipal Solid Waste
MWMS	Mobile Workforce Management System
NIST	National Institute of Standards and Technology
NMS	Network Management System
NPV	Net Present Value
NSO	National Statistic Office
nZEB	Nearly Zero Energy Building
O&M	Operation and Maintenance
OLTC	On-Load Tap Changer
OMS	Outage Management System
PCC	Point of Common Coupling
PDP	Power Development Plan
PEA	Provincial Electricity Authority
PEF	Primary Energy Factor
PF	Power Factor

PFChar	Power factor characteristic
PPA	Power Purchase Agreement
PPP	Purchase Power Parity
PTR	Peak Time Rebate
PV	Photovoltaic
Q(U)	Voltage-dependent reactive power
RE	Renewable Energy
REF	Reference Building
RES	Renewable Energy Standard
RTP	Real-Time Pricing
RTTR	Real Time Thermal Rating
RUT	Random Utility Theory
SCADA	Supervisory Control and Data Acquisition
SEA	Southeast Asia
SEC	Specific Energy Consumption
SEI	Stockholm Environment Institute
SGAM	Smart Grid Architecture Model
SGTF	Smart Grid Task Force
SOC	State of Charge
SOE	State-Owned Enterprise
SPP	Small Power Producer
SVR	Step Voltage Regulators
TES	Thermal Energy Storage
THD	Total Harmonic Distortion
TIEB	Thailand Integrated Energy Blueprint
TOU	Time of Use
UQDroop	Voltage Reactive Droop Control
USA	United Sate of America
V2B	Vehicle to Building
V2G	Vehicle to Grid
V2H	Vehicle to Home

V2V	Vehicle to Vehicle
VAT	Value-Added Tax
VPP	Virtual Power Plant
VRE	Variable Renewable Energy
VSPP	Very Small Power Producer
WAMS	Wide Area Monitoring System
WAPC	Wide Area Protection and Control
WASA	Wide Area Situation Awareness
WMS	Workforce Management System
WTP	Willingness to Pay

- empty page -

Appendix 1

Lesson learned from smart grid pilot projects in the EU

Table A.1 Lesson learned from smart grid pilot projects in the EU

Domain	Project	Year	Country	Key Findings
Home Application and Demand Response	Model city of Mannheim (Energy Bulter)	• 2008 - 2012	• Germany	• The project is implemented in an urban area in Mannheim, Germany. The project focuses on the energy management device with consumer in response to the price signal • Load shift of 6-8% in low tariff period and load management potential of 0.1 kW per household • About 80% of participating customers said that they would not pay for the provision and display of electricity consumption data. • Almost 20% of installed capacity can be used as positive balancing power through switch-off or delay switch-on for 30 mins.
	eTelligence	• 2009 -2012	• Germany	• There are 650 households with IHD for real time electricity monitoring with smart meter • There is 13% monthly reduction of energy consumption for participating consumer and 12% monthly reduction of consumption in the expensive period for participating consumer. • It demonstrates the thermal energy system in particular cold-storage depots and block type thermal power station. It can save up to 8% of their normal electricity costs • It is suggested that telecommunication expertise is necessary.
	Energy demand project	• 2007-2010	• UK	• A large-scale trial of 18,000 households showed the saving from smart meter with IHD about 3% and up to 11% • The saving was found to be generally durable rather than short term. • Saving are not guaranteed simply by implementing a particular type of measure but the impact depends on how it is implemented.
Smart meter	WEB2ENERGY	• 2010-2012	• Germany, Netherlands, Austria, Poland, Switzerland	• The project Web2Energy is directed to implement and approve all three pillars of Smart Distribution, smart metering and smart energy management. • This project included three days ahead tariff zones (green, red, and yellow) produced by the Virtual Power Plant on the basis of spot market electricity price forecasts and wind and sunshine intensity. • During the first 3 months, energy saving represented on average 3% of the household's daily consumption • The daily peak was reduced by approximately 5% by shifting heavy demand from red to green phases.

Table A.1 Lesson learned from smart grid pilot projects in the EU (Continued)

Domain	Project	Year	Country	Key Findings
Energy Storage	Grow-DERs	• 2009 – 2011	• France, Germany, Estonia, Netherlands	• GROW is Grid reliability and Operability with Distributed generation using flexible storage. • The current market shows that the application of storage systems is technically very attractive but economically not yet viable. • Uncertainty in legislation is a barrier to the development of grid-connected storage application
	Grow-DERs	• 2009 – 2011	• France, Germany, Estonia, Netherlands	• Industrial player needs to invest in early demonstration projects to be involved in this market in the longer term. • A new commercial software for the techno-economic assessment of grid connected storage systems was developed.
Energy Storage	Millener	• 2009	• France	• There is 325 target number of residential homes to have solar generation and energy storage systems installed as part of the Millener project. • The project has already helped validate a range of benefits for all stakeholders. • The homeowner is offering the flexibility of their renewable energy production to help balance the grid
Electric Vehicle	Mini Berlin	• 2008 - 2010	• Germany	• The project focuses on EV and 50 MINI EV cars are demonstrated (35 kWh, range ~ 180-200 km, max speed 152 km/h). • Using V2G application for ancillary service to the grid. • Home charging and public charging
	EDISON	• 2009 - 2011	• Denmark	• Further attention needs to be given to technical barriers to the use of EVs to provide grid services (e.g. connected converters and inverters will emit harmonic distortion into the power system; switching on and off charging can lead to fast voltage changes causing flicker problems) • It is not likely to see V2G functionalities in EVs on the market for some years yet Chargers currently on the market do not have V2G functionalities.
Building to Grid (B2G)	Building to Grid (B2G)	• 2010- 2013	• Austria	• The project integrated the building into the smart grid and investigate how the building behave. • Active building has potential for smart grid but requires building automations and information technology

- empty page -

Appendix 2

Overview smart grid roadmap in Thailand

Table A.2 Overview smart grid roadmap in Thailand

Roadmap	Demo and Pilot project	Short term (2022-2026)	Medium term (2027-2031)	Long term (2032-2036)
National Roadmap	• Set up working group for action plan • Set up the agency for monitoring smart grid roadmap and define the framing of annual budget • Set up the working group for communicate and exchange information between three utilities • Set up the working group for improving regulation and standard for electricity generation from renewable energy • Grant scholarship to universities for smart grid capacity building research fund for initial smart grid research • Promote and acknowledge of smart grid to public agencies as well as publicize the importance of smart grid awareness to people	• Grant research fund for smart grid research such as HEMs/BEMs/FEMs, demand response (DR), micro grid and energy storage • Study and review the appropriate technology from pilot projects to define the smart grid development direction in the next stage	• Support real time pricing (RTP) or at least various TOU programs • Set up the forecast of electricity generation and energy storage center • Deploy the local content measure of smart gird investment by government project • Deploy the support measure to encourage private sector for software and hardware of smart grid development in the country • Support EGAT to invest and develop fundamental structure for generating and distribution system to serve the smart grid system • Support PEA and MEA to invest and develop fundamental structure for distribution system of smart grid	• Formulate the policy for EGAT to develop smart charging for electric vehicle, Renewable energy forecast technology, High volt transmission technology and EHV/FACTS, Load response management technology, electricity demand management • Formulate policy to three utilities for investment smart grid technology such Energy storage, Smart charging technology, Micro grid, Demand response • Formulate support and incentive policy for all customers including residential, commercial building, factory and industry to install technology for energy management efficiently

Table A.2 Overview smart grid roadmap in Thailand (Continued)

Roadmap	Demo and Pilot project	Short term (2022-2026)	Medium term (2027-2031)	Long term (2032-2036)
EGAT	• Maehongson microgrid project consists of solar power (0.5MW), hydropower (11MW), diesel generator (4.4 MW), Battery energy storage system (1 MWh • Battery energy storage projects in Chaiyapum city (16 MWh) and Lopburi city (21 MWh).	• Pilot project implementation and assessment on energy storage and EV • 115 kV substation automation implementation and optimized loss and voltage control, 500 kV equipment monitoring &risk analysis • Deployment of EGAT MDMS, RE monitoring, Smart charging • Identify the potential of battery and pump hydro storage, WAPC study and identify vital state point, RE forecast • Promote RE generation and community plan and ICT infrastructure • Improvement /structural harmonization of grid codes, Network data standardization and integration •	• >115 kV substation and IPP&SPP implementation, optimized 115 kV active power control, <500 kV, IPP&SPP monitoring risk analysis-reliability issue • Integration of EGAT MDMS to EMS • Expansion of community power plant + ICT implementation for RE • Technical harmonization of grid codes • Smart charging implementation • Integration of RE forecast to EMS • Full-scale deployment of energy storage system • V2G technology phase I • GIS phase I (for 500 kV) • FACTS for <500 kV substation Phase I + Full scale EMS Phase, FACTS/HVDC for 500 kV systems + EMS improvement	• Full scale deployment to the network • Risk analysis improvement corporate issue • Full scale integration of RE forecast to EMS • Pump-hydro storage in neighboring countries • V2G technology Phase II • Full scale GIS and database integration • GIS phase II (for <500 kV), • FACTS for < 500 kV substation Phase II + Full scale EMS Phase II
PEA	• Microgrid in Mae Sariang city • Microgrid in Koh Kood, Koh Mak in Trad Province • AMI pilot project in Pattaya city • EV charging station in Bangkok, Huahin and Nakornratchasima	• Establish the core smart grid&engage consumer, and enable a complete set of smart grid capabilities • Introduce smart grid technologies to the consumer • Electric Vehicles pilot • Mobile workforce management national rollout • Smart grid analytics national roll out	• Expand smart grid infrastructure and capabilities nationwide • Support and encourage consumers to adopt smart grid technologies • Mobile workforce management national rollout • Smart grid analytics national roll out	• *Expand smart grid infrastructure and capabilities nationwide* • *Support and encourage consumers to adopt smart grid technologies* • Mobile workforce management national rollout • Smart grid analytics national roll out
MEA	• DMS deployment in Bangkok • Transformer load monitoring pilot project for 30 units in Bangkok. • Smart meter pilot project of 20,000 units in Bangkok • 100 EV charging stations in Bangkok	• Making progress on the existing projects • Implementing pilot projects • Enhancing service excellence	• Facilitating grid connected renewable energy source • Promoting customer engagement in energy management in all sectors • Preparing for advanced smart grid technology • Developing infrastructure for smart community	• Investing in advanced smart grid technology • Promoting participation in full scale energy management in all sectors • Expansion of smart community project to cover total responsible areas.

- empty page -

Appendix 3

A comparison of smart grid roadmap of the country in the Southeast Asia

Table A.3 A comparison of smart grid roadmap of the country in the Southeast Asia

Country	Electrification rate (%)	Smart grid plan	Target of smart meter roll out	Key findings of smart grid plan	Current smart grid activities
Brunei	100	N/A	N/A	N/A	N/A
Cambodia	65	N/A	N/A	N/A	N/A
Myanmar	44	N/A	N/A	N/A	N/A
Indonesia	91	Yes	• Indonesian vision for the future - a network of integrated systems that can monitor and heal itself • Advanced Metering Infrastructure (AMI): selected customers with 10,000 smart meters in trial projects via Power Line Communication	• Increasing penetration of renewable energy, diversification in electricity generations, reduction in carbon emission • Enhanced compatibility of electricity network with increased penetration of renewable energy • Communications between the network and various types of generations • Providing services for various consumers' electricity needs, mainly in remote and isolated areas	• Smart Microgrids on some islands (Nusa Penida, Morotai, Karimun and Sumba)
Laos	92	Load dispatching center	N/A	• There will be distribution control center in Sisakhet which is expected to complete in 2017 • There are four location of distribution reinforcement developed in 2016-2017 in Vientiane, Khammounce, Savannakhet and Luang Prabang	Load dispatching center project in Sisakhet
Malaysia	98	TNB's 25 years Electricity Technology Roadmap	• Pilot project of 1,000 smart meters in two areas of Malaysia • Smart meter roll-out is expected to be completed by 2023	There are 3 phases of smart grid implementation • Phase 1 (2010-2011): Improve Reliability • Phase 2 (2011-2013): Increase customers participation and improve energy efficiency • Phase 3 (2011-2015): Reducing CO_2	• An installment of 1,000 smart grid advance meters both in Putrajaya and Malacca • Kema Microgrid

Table A.3 A comparison of smart grid roadmap of the country in the Southeast Asia (Continued)

Country	Electrification rate (%)	Smart grid plan	Target of smart meter roll out	Key findings of smart grid plan	Current smart grid activities
Philippines	88	Yes	• 140,000 meters by 2016 • Deploy smart meters with In-home Display (IHD)	• This first phase of The Manila Electric Company's long-term smart grid vision is integrating "smart intelligence" into the electric distribution network to help consumers better manage their electricity consumption.	• Advanced SCADA Project • Overall Command Center Project • Feasibility Study for First Smart Grid Substation in Philippines • Renewable Energy Integration
Singapore	100	Yes	• Intelligent Energy System project of 2,000 smart meters in a Housing Development Board estate with in home display	• Phase 1: Developing the enabling infrastructure (2010-2012) • Phase 2: Rolling out smart meters to assess applications and consumer response (2012-2013)	• Advanced Metering and Communication Infrastructure • Demand response management systems • Management system for distributed energy source • Experimental Power Grid Centre • Pulau Ubin Microgrid
Thailand	99	Thailand Smart Grid Roadmap and utility roadmap (EGAT, MEA, PEA)	• A pilot project of 110,000 smart meter in Pattaya started by 2018	The combination of smart energy, smart life, and smart community • Stage 1: Laying the foundations (2012-2016) • Stage 2: Large scale integration (2017-2021) • Stage 3: Optimal stage (2022-2026) • Stage 4: Ultimate stage (2027-2031)	• MEA smart grid roadmap including SAS/DAS, SCADA-DMS, Smart meter, EV related business development and technical impacts • Mae hong son smart grid national pilot project • Renewable energy generation developing project at Kood island and Maki island

Table A.3 A comparison of smart grid roadmap of the country in the Southeast Asia (Continued)

Country	Electrification rate (%)	Smart grid plan	Target of smart meter roll out	Key findings of smart grid plan	Current smart grid activities
Vietnam	98	Decision No. 1670/QD-TTg issued on 8 November 2012 provide a plan for smart grid development in Vietnam	• Pilot project of EVN and world bank approximately 10,000 meters	Three phases of implementation as follows: • Phase 1 (2012-2016) Preparing regulation and technique specification • Phase 2 (2017-2022) Installing the SCADA/EMS, Extend the AMI, Implementing the Demand response, Integrating the DG in LV and MV grid, smart home and smart city • Phase 3 (after 2022), Continue to communication distribution infrastructure program and Applying to electrical system from smart grid achievement	• ToU meter program and load demand research • Project “10 Years road map for smart grid distribution in Vietnam” including smart metering, customer program and distribution automation • SCADA/EMS project on distribution grid management • Installation of electronic meter project • Electric vehicles in tourism and large cities (Cua Lo, Sam son, Hai phong, Hanoi, and Hochiminh) • AMR project in Ho Chi Minh City by EVN SPC • MiniSCADA project in Da Nang City by EVN CPC • Wide-area surveillance system in 500kV transmission networks via Optical Ground Wires

Appendix 4

Conference paper on the barrier of consumer behavior change to the demand response in the smart grid: Case study of Thailand

BARRIERS OF CONSUMER BEHAVIOR CHANGE TO DEMAND RESPONSE IN SMART GRID: CASE STUDY OF THAILAND

Jirapa Kamsamrong[1,2]*, Christoph Menke[1] and M. Norbert Fisch[2]
1: Energy Technology and Technical Building Services
Trier University of Applied Sciences
Schneidershof, D-54293 Trier, Germany
e-mail: jirapa.kamsamrong@gmail.com
web: http://hochschule-trier.de

2: Institute of Building and Solar Technique
Technology University of Braunschweig
Mühlenpfordt Str.23, D-38106 Braunschweig, Germany
e-mail: prof.fisch@egs-plan.de
web: http://igs.tu-bs.de

Keywords: Demand response (DR), Smart grid, Consumer behavior, Prosumer

Abstract

A smart grid is a form of energy system transition from centralized to decentralized, from traditional consumer to active consumer or prosumer, and from one-way communication to two-way communication. The current development of smart grid in Thailand is being more active in the interoperability technology dimension, especially in the generation and distribution system, but the consumer and an energy market design integration is still absent. This paper aims to identify the key barriers, both from an institutional and consumer point of view, which might prevent demand response implementation. The study included a stakeholder interview and household survey. The study found that market regulations and consumer perception are expected to be the main obstacles that could limit the demand response deployment and the full prosumer capacity. Realistic behavior assumptions are greatly needed in order to design an effective dynamic pricing policy to avoid huge investment in non-active consumers, e.g. smart meter rollout. The proactive policy, combining technology, social science, and market mechanism dimensions, would enhance the traditional consumer role to be an active consumer and prosumer of the smart grid system.

1. INTRODUCTION

The centralized system is a traditional power system that allows only the utilities industries to transmit electricity one way to the consumer. Energy transition enables the centralized system to become a decentralized system with long-term structural change [1]. A smart grid is a form of energy transition that empowers traditional consumers to become active consumers and "prosumers" [2]. The demand response (DR) program is one of the smart grid policy drivers with varying tariffs and automatic response technology that would encourage consumer behavior change [3].

Whereas smart grid technology is being implemented worldwide through the provision to consumers of smart meters and a DR program, consumer behavior remains an uncertain factor in smart energy development, due to the lack of attention placed on integrating social aspects into emerging technologies. Several studies have indicated that the non-technical dimension is one of the reasons why policy implementations related to smart grid technology has failed so far in areas such as public safety hazards, consumer behavior awareness, and institutional complications [2],[4],[5]. The social dimension and market mechanism integration have taken a more active role in smart grid development.

2. CONTEXT OF SMART GRID

There are many definitions around the world for the term smart grid, depending on the area of focus. The term 'smart grid' was proposed by the Electric Power Research Institute (EPRI) in 2002. The EPRI defines smart grid as "a new type of highly integrated power grid, which is the combination of modern advance sensing and measurement technology, information technology, communication technology, control technology and physical power system" [6]. The early definition of smart grid development mainly focused on technology in electrical systems that had a stable and reliable operation of the system [7].

Under the centralized electricity system, consumers are forced to be as "dump" [8] or have a non-active role but have the potential to be involved in decision-making in responsive price signal and behavior change. Consequently, the consumer behavior dimension has been included into the smart grid definition by the European technology platform, who state that the "electricity network that can intelligently integrate the behavior and actions of all users connected to it such as generators, consumers, and those that do both, in order to efficiency deliver sustainable, economic and secure electricity supplies" [9]. In conclusion, a smart grid refers to an energy system transition from centralized to decentralized, from traditional consumer to active consumer or prosumer, and from one-way communication to two-way communication.

3. CONSUMER ROLES IN SMART GRIDS

Smart grids enable traditional consumers to become prosumers who can generate and consume electricity, and active consumers who can manage their electricity consumption depending on price signal [10],[11]. The traditional consumer still exists but there are fewer traditional customers in the smart grid. The challenge of consumer role transition from the traditional consumer to the active consumer has raised critical questions regarding the misunderstanding or having over/under expectations of the technology benefits, consumer privacy, increased control by energy companies, and the fear of dangerous electromagnetic radiation, [2],[4],[12],[13],[14] despite this not being the reality. Realistic consumer assumptions, which consist of several elements interlinked to one another as social practice, would enhance the introduction of such effective emerging technology [15],[16].

The new era of integrating technologies and consumer behavior is a challenge for future smart grid development. Smart residential building, electric vehicle (EV), and solar rooftops are potential technologies through which the traditional consumer can become a prosumer. The integration of smart building as an EnergyPLUS building with a solar rooftop and EV in a smart grid concept would enhance the prosumer's role and can generate excess energy that can be fed to the grid or sold to neighboring households as distributed generation (DG) [17]. However, prosumers might face enormous problems in getting connected to the grid due to financial and legal limitations preventing them from gaining full access to distribution and transmission lines compared to larger-scale projects [6]. There is clearly a need for regulatory and market mechanisms to ensure fair grid access for small and medium prosumers [18].

4. DEMAND RESPONSE AND DYNAMIC PRICING

The demand response (DR) program is one of the policy drivers in the smart grid that can encourage traditional consumers to be more active. The greatest advantage of the DR program is that it can encourage consumers to reduce their consumption during the peak periods under the dynamic pricing signal. The big advantage of the DR program is to reduce the installation of peaking generation capacity by avoiding energy costs associated with the peak load, as well as avoiding transmission and distribution capacity costs [3],[19]. The load reduction will come mainly from commercial and industrial users due to their higher electricity consumptions [12],[13].

The DR program has to work with Advanced Metering Infrastructure (AMI), called a smart meter. Smart meters consist of telecommunication technologies and clip-on display units that enable the automatic reading of meters and the application of the demand side management program [4],[8],[13]. In addition, the great advantage of smart meters for the utilities industry is to be able to identify faults remotely, improve accuracy, and avoid mistakes that can be made when electricity consumption is recorded manually [4].

Adopting a DR program cannot be effective without the incentive of varying electricity prices [20]. Most countries that have installed smart meters do not yet have a dynamic pricing design in place. There is a need to monitor consumer behavior during a period of time to establish the most appropriate approach to specific consumer type, as well as the electricity mechanism situation [14],[19]. Several flexible electricity tariffs are applied to the demand response, for example: time of use (TOU), real time pricing (RTP), critical peak pricing (CPP), and peak time rebate (PTR). It should be noted that TOU is not dynamic pricing, as it is not dispatched based on the changes in actual wholesale market prices [21]. The TOU and CPP rate structures do not guarantee the reduction of the peak if the customers can afford the high electricity price during peak or critical days, while the electricity bill of a consumer in the PTR program remains the same in the absence of peak load reduction. The total demand response of a PTR scheme is likely to be greater than for a CPP scheme due to the consumer not being forced to participate [3],[19].

A dynamic pricing structure creates more difficulties for the utilities industry and the energy market regulator because it is more complex than a fixed tariff and any TOU tariff. However, dynamic pricing would lead to greater awareness and behavior change on the part of the consumer.

5. METHODOLOGY

With smart grid development emerging worldwide, technology and economic dimensions have been raised as the main components for its implementation, while the social component has largely been overlooked. In a developing country like Thailand with a monopoly electricity industry market, the deployment of a smart grid in Thailand is crucial due to the lack of attention placed on integrating consumer behaviour into a DR program and the electricity market context. To date, there has been no concrete research conducted on the social dimension of smart grid development in Thailand. The identification of barriers would lessen the unexpected obstacles to demand response development in the future. In order to examine the smart grid development situation in Thailand, we divided participants into two groups: stakeholders and consumers.

The stakeholders were interviewed using semi-structured interviews, which allowed them to talk freely about smart grid development and possible barriers that might prevent the DR deployment in Thailand [4],[20]. The consumer survey used the two-stage mental models [4],[22] that examined the consumers' prevalence of the beliefs expressed and their attitude toward DR and smart meter development.

5.1 Stakeholder interview and household survey design

The criteria for selecting stakeholders started through the consultation of experts in smart grid development in Thailand. Further stakeholders were found using the snowball sampling method. The interviewees represented 16 stakeholders including: 4 policy makers, 4 utlities, 4 universities, 2 NGOs, and 2 private sector actors. The semi-structured nature of the interviews gave stakeholders the opportunity to first present their opinions on smart grids without being guided too strongly. The interviews took between 0.5-1 hour on average. The interview questions focused on three main dimensions, which were: policy and institutional arrangement conflict, consumer engagement, and technology development.

Besides the stakeholder interview, the household survey was conducted with 50 participants in Pattaya city where the smart grid and smart meter will be implemented in the near future. The criteria for sampling participants were based on the convenience sampling method**.** The criticism of this method is that it is subjective and is not representative of the entire population. However, it allows preliminary research to be conducted and for basic data to be obtained within a limited budget and time frame [23]. The survey took 10-15 minutes on average. The household survey questions were open-ended and focused on their perception of smart meters, as well as mulitple choice questions on where they had heard about smart grids. Finally, yes/no questions were asked to determine if they thought a smart meter could help them reduce their electricity bill, whether they were aware of privacy issues, and to determine who was the family's decision maker when it came to electricity consumption.

6. RESULTS AND DISCUSSION

6.1 Smart grid development in Thailand

Thailand's electricity supply relies mainly on natural gas at approximately 60% of its total electricity generation. The increase of renewable energy is still limited because the electricity distribution technology and transmission system were not designed to serve renewable energy at the beginning. Smart grid technology enables the electricity system to be more flexible, managing electricity demand and supply, especially variable renewable energy which could reduce the building of new power plants to serve the demand as was done in the past. The majority of smart grids in Thailand have begun from utilities industries. Thailand's Energy Policy and Planning Office (EPPO) under the Ministry of Energy developed a national smart grid master plan in 2015 following the smart grid roadmap made by the utilities industry, which was developed in 2012. It is quite uncommon for a national energy policy to be developed after the utility industry develops a roadmap but was due to the institutional arrangements conflict. The Ministry of Energy as a national policy maker agency had to frame the national smart grid roadmap in accordance with each of the projects from utilities industries under the vision to "Encourage electricity supply adequately, efficiency, sustainability, quality service, and maximize benefit to the country" [24].

The status of smart grid development in Thailand is under preparation and still in its pilot stage, which mainly focuses on generation and distribution systems in order to address the interoperability technology [25],[26],[27]. The Provincial Electricity Authority (PEA) and the Metropolitan Electricity Authority (MEA) have smart grid roadmaps for consumer engagement, which aim to enable consumers to take control of their energy usage and bills through the use of digital information and technology. This would offer consumers more energy service choices, and ultimately create a new smart way of life for them. However, the consumer engagement program on DR requires regulation and price mechanisms to empower the DR program. Smart meters are a key factor for DR development and are an area of focus for the Thai utilities industry. The PEA has a smart meter pilot project in Pattaya city (in Chonburi province) at approximately 116,000 units in 2018 [26]. This pilot project will be preliminary assessed in terms of its analytics platform, advanced analytical model tools, and system implementation. If the pilot project in Pattaya succeeds, there will be another 18 million AMI units installed by

2036. Nonetheless, there is no concrete plan to integrate the social dimension with the electricity market to induce behavior change regarding the DR program. The consumer dimension should be taken into consideration in the early stages of the project in order to learn about, and prepare for the policy and incentives scheme, according to the characteristics of each consumer group [28].

6.2 Instituional arrangement

Thailand's electricity industry market has been a state-owned enterprise (SOE) since the 1980s [29],[30]. The Electricity Generating Authority of Thailand (EGAT) is the main electricity generator, while the Provincial Electricity Authority (PEA) and the Metropolitan Electricity Authority (MEA) are the only two distributors in the country. The MEA is responsible for electricity distribution in Bangkok, Nonthaburi, and Samutprakan provinces, while the PEA is responsible for all other provinces in the country. Following the above-mentioned boundaries of responsibility, consumers have no other alternatives; they have to buy electricity from the MEA and PEA. Consequently, the tri-poly SOEs have control over all electricity generation, transmission, distribution, and retail services in Thailand [31].

The structure of the electricity market has a direct relationship to competition improvement and changes in the assess ownership. Liberalization of the electricity market is highly required to drive up the importance of a smart grid system in terms of increased interconnection, robust regional trade, and heightened transparency [9],[32]. Since 1992, there has been an attempt to restructure the privatization to liberalization market in Thailand by introducing the Independence Power Producer (IPP) and Small Power Producer (SPP). Nevertheless, the reform was opposed due to the inappropriate regulatory framework. Moreover, there was an aftershock as a result of the 2000 California energy market crisis, which resulted in consumers becoming concerned about gaming and market power abuses that could lead to uncontrolled high electricity prices [31],[33].

The stakeholders were asked "Is the current electricity industry market in Thailand a barrier to smart grid development?" Most stakeholders (67%) responded that the existing electricity market can enable smart grid implementation but needs the help of policy drivers, financial support and cooperation between utilities industries. Currently, the PEA and MEA are under the Ministry of the Interior, whereas EGAT is under the Ministry of Energy. The mismatch in the organizational arrangement could impact effective governance. 33% of stakeholders indicated that a liberalized electricity industry would allow smart grid development to be more efficient in terms of market mechanism competition. The study by Jacopo et al. suggests restructuring organization through two main policy alternatives: (i) "ownership unbundling" so that there is a separation of powers in companies that control both energy generation and transmission, and (ii) the introduction of Independent System Operators (ISO) [8]. There is a possibility to restructure the Thai electricity market but it needs a strong policy signal from the government. Market reform is very complex, in particular because of legal obstacles and strong opposition from the utility industry's labor unions (see Table 1).

Table 1 Example quotes showing interviewees' views on smart grid development in Thailand

Interviewees quotes
"The liberalization of the electricity market would allow smart grids to be implemented efficiently."
"There is an institutional conflict issue in the electricity industry market. Liberalization of the market will not happen within the next 10 years."
"It is possible to restructure the institutional arrangement of the MEA, PEA, and EGAT, but it would be very complex."
"The current electricity market is not a barrier for smart grid development but the existing market needs to be designed for the pricing schemes"
"Liberalization of the electricity market is not a guarantee of low electricity prices."

In summary, a smart grid can be implemented in both monopolistic and liberalized markets but it requires the roles of energy providers, market mechanisms, and consumer acceptance to be well-defined and can draw up to the optimum point where every player gets fair and appropriate benefits under the energy market structure [32]. The major apprehensions in regards to the restructuring of the electricity market from the stakeholder interview were: grid stability, supply security, electricity prices, consumers' satisfaction, and lowering the governance burden. The Energy Regulatory Commission (ERC) has an important role in increasing market competition in accordance with regulatory capacity if there is a definitive direction toward liberalization for power sector reform in Thailand in the future.

6.3 Lack of electricity pricing scheme design as a barrier

Hypothetically, the DR program offers electricity prices sensitive to changes in consumer demand. According to the electricity industry market in Thailand, the retail price for the residential sector in Thailand has two pricing schemes, regression and TOU rate. The retail electricity price comprises three components including base tariff, automatic adjustment mechanism (Ft), and VAT [34]. The consumers were asked if they had heard of TOU before. Most of the respondants (76%) answered that they had never heard of TOU before and the 24% of respondants who had heard of TOU did not use it because of the high installation cost of the meter (approximately 425-500 EUR). The initial high cost of the measurement device is one of the barriers that can prevent the DR implementation regarding the TOU scheme. Several smart grid pilot projects have shown that the consumers prefer the TOU tariff rather than dynamic pricing, even though dynamic pricing induces major changes in the consumer's energy consumption pattern [14],[35],[36]. This is because the TOU mechanism is simpler than dynamic pricing. The TOU tariff can remind customers as a "traffic light" or by SMS to ensure that they know when the high price period is [14].

Moreover, the respondants were asked if the alternative pricing schemes would change their behaviour pattern. The results show that 60% would stay with their the existing rate and 32% would prefer the rebate payment if they could reduce their electricity consumption from the baseline. Only 8% of respondents chose the CPP rate, as shown in Figure 2. The respondants were asked (using the semi-structured approach) about the reason for not choosing the CPP rate. Most of the respondants believed that it was like some sort of punishment, which they would be forced to accept and was unfair to low-income consumers compared to high-income consumers. As a result, the CPP could be applied to high-energy consumption and high-income groups while the PTR would be an appropriate approach for low- and midle-income residents with opt-in/out participation. Ahmand et al., also indicate that although real time pricing (RTP) is the purest scheme, it may not be the best scheme for low mass electricity consumption (e.g. the residential sector), but rather to majority mass market electricity consumers [21].

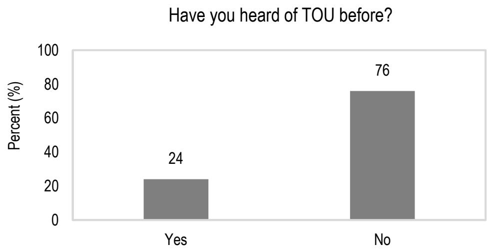


Figure 1 Consumer perception of TOU

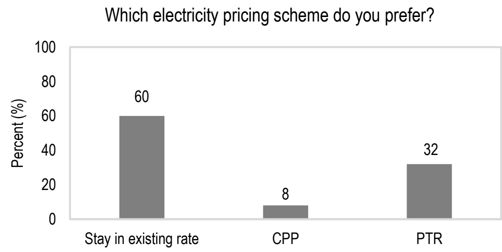


Figure 2 Consumer conception of alternative electricity pricing schemes

Presently, Thailand has implemented the DR pilot project by EPPO called "DR 100" for 100 households but only uses direct control for air conditioners, without giving the dynamic pricing application [37]. Concerning direct load control as "Big Brother" or "Nag Factor" without incentives could limit the consumer's satisfaction and willingness to support the technology [4],[38]. The DR program on households that did not have any specific targets or rewards did not have any detectable effect on consumption [36].

6.4 Consumers as a barrier

Consumer behavior is one of key factors for DR implementation in many studies [2],[4],[12]. The consumer dimension should be taken into consideration at the early stage in order to learn about, and prepare for the policy and incentives based on the consumer group, e.g. low-income [28]. According to the household survey, 92% of respondents had neither heard of, nor understood the smart grid and smart meter, as shown in Figure 3. Only 8% had heard of the smart meter and smart grid but still misunderstood its benefits. The most common misunderstanding about the smart meter (from 60% of respondents) was that it could help them reduce electricity consumption (which is consistent with the study conducted in the EU and USA [13,14]), 36% of respondents thought that it could shut down electricity automatically, and 4% of respondents had no idea about its benefits, as shown in Figure 4. The misunderstanding of technology's abilities or having greater expectations than the reality is one of reasons the smart grid implementation has failed.

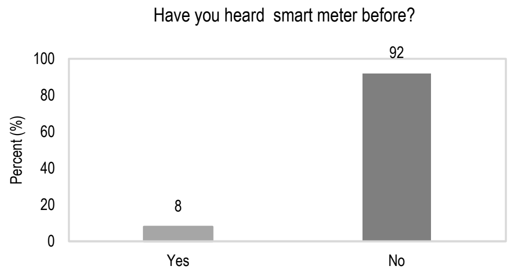


Figure 3 The consumer perception of smart meter

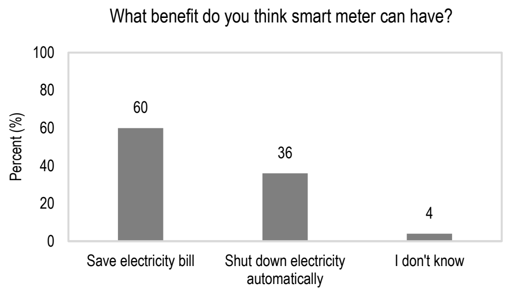


Figure 4 The consumer perception of smart meter benefit

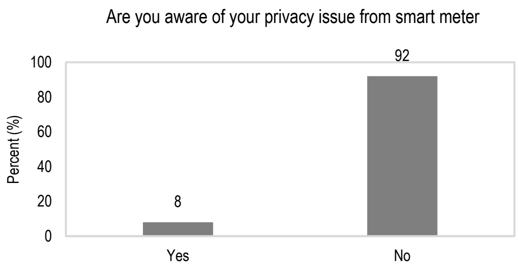


Figure 5 The consumer concern on privacy issue

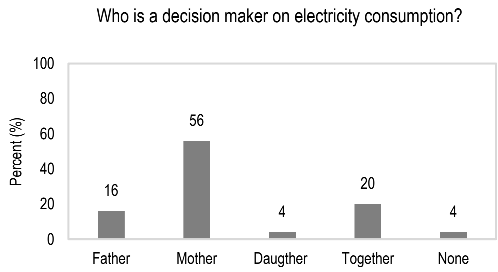


Figure 6 Gender as decision maker for electricity consumption in the family

The stakeholders expected that there would be no privacy issues regarding the smart meter on the part of the consumer, which is consistent with the household survey result. Approximately 92% respondents were not aware of their privacy, as shown in Figure 5. One consumer expressed that "I am not afraid that they will monitor my electricity consumption data from smart meter but I would worry if a stranger got my phone number, and had accesss to my private life". This implies that the consumers lack knowledge about the risks of the smart meter in terms of privacy issues and data protection, as their data could be accessed by hacking the smart meter. Moreover, the consumers were asked what type of support they would need from the government to reduce their electricity consumption. 60% of respondants answered that the government should lower electricity prices, which indicates that Thai consumer perception toward the smart grid is not to engage and change themselves to price signal, but rather request subsidies from the government. In other words, consumer perception toward new technology is not yet well in place.

As a result, the DR deployment in Thailand should seriously emphasize the realistic behavior assumptions dimension, which can handle consumer engagement, behavior, and perception regarding DR deployment. The respondents were also asked who made decisions on electricity consumption in their household. The results indicated that the mother (in 56% of cases) was the decision maker in the family when it came to electricity usage, followed by joint decision making by both the mother and father (20% of cases), as shown in Figure 6. Consequently, the strategy to educate consumers about behavior change in the residential sector should focus on women rather than men. The study of MECON indicates that men are better able to make decisions on electricity consumption compared to women, while women make decisions on fuel use for cooking and lighting, e.g. to turn off the light [39]. Nevertheless, the increasing awareness of energy efficiency needs to target everyone in order to induce the family members to reduce their electricity consumption.

7. CONCLUSIONS AND RECOMMENDATIONS

The current smart grid development in Thailand is being more active in the interoperability technology dimension especially in generation and distribution system, but the social dimension and energy market design are still absent. Thailand's electricity industry market is currently a monopoly; however, a liberalized energy market could offer dynamic and real time pricing. Concerning the implementation of a complete smart grid system, a liberalized energy market would allow consumers and energy providers to achieve maximum benefits from smart grid implementation. The existing Thai electricity industry market can also partly implement smart grid aspects like a DR program but limits the full potential of the "prosumer" concept. It needs an institutional arrangement restructure and the development of pricing schemes to trigger consumer behavior changes under the existing electricity market. The government and the utilities industry will have a leading role in establishing linkages to the decentralized initiatives, which does not only focus on the technological dimension but also on more innovative political, social, and economic approaches [40].

Moreover, a lack of information on the public's awareness, perception, and acceptance of such a new technology could prevent consumer support and reduce their satisfaction level. Consumer uncertainties regarding their misunderstanding of the technology's ability or having over expectations compared to the reality would be one of reasons that smart grid implementation could fail. If the consumer perception toward technology goes wrong, it will take a long time to correct it and rebuild trust to accept and support the technology. The social gap must be seriously taken into consideration during the pilot stage, where potential obstacles for the emerging new technology and related price mechanisms can be foreseen.

The empirical question on how the residential sector (with different income levels) could react to the DR could be preliminarily determined in the pilot stage through consumer behavior. Larger samples for the household survey are needed for future studies on consumer behavior and electricity pricing experiments. This kind of survey needs financial support to be carried out. Realistic assumptions of consumer behavior are needed in order to establish a realistic baseline load for each consumer group and design an effective dynamic pricing policy to avoid huge investment to non-active consumers during a smart meter rollout. The government, utilities industry, and regulators should clarify the cost benefit of smart grid or smart meter to the consumer and bring the implementation of the technology in line with consumer behavior and expectation levels, as well as communicate to the consumer both the benefits and costs of the technology before its implementation. A proactive policy, which includes all aspects, such as technology, and social and energy market mechanisms would enhance smart grid development in Thailand in the future.

8. ACKNOWLEDGEMENTS

The authors would like to acknowledge their sincere appreciation to all stakeholders for providing useful data during the interview and respondents of the household survey in Pattaya. In addition, the authors would like to thank the Deutscher Akademischer Austauschdienst (DAAD) for its financial support through the Ph.D. scholarship for Miss Jirapa Kamsamrong.

9. REFERENCES

[1] World Energy Council, Global energy transition, (2014).

[2] Naus, J., Spaargaren, G., Vliet, J. M. B., & Horst, M. H. (2014). Smart grids, information flows and emerging domestic energy practices. Energy Policy, 68, 436-446.

[3] Alexander, R. B. (2010). Dynamic Pricing? Not So Fast! A Residential Consumer Perspective. The Electricity Journal, 23(6), 39-49.

[4] Krishnamurti, T., Schwartz, D., Davis, A., Fischhoff, B., Bruin, B. W., Lave, L., & Wang, J. (2012). Preparing for smart grid technologies: A behavioral decision research approach to understanding consumer expectations about smart meters. Energy Policy, 41, 790-797.

[5] Döbelt, S., Jung, M., Busch, M., & Tscheligi, M. (2015). Consumers' privacy concerns and implications for a privacy preserving Smart Grid architecture: Results of an Austrian study. Energy Research & Social Science, 9, 137-145.

[6] Yuan, J., Shen, J., Pan, L., Zhao, C., & Kang, J. (2014). Smart grids in China. Renewable and Sustainable Energy Reviews, 37, 896-906.

[7] Blumsack, S., & Fernandez, A. (2012). Ready or not, here comes the smart grid!. Energy, 37(1), 61-68.

[8] Torriti, J., Hassan, G. M., & Leach, M. (2010). Demand response experience in Europe: Policies, programmes and implementation. Energy, 35(4), 1575-1583.

[9] Connor, M. P., Baker E. P., Xenias, D., Balta-Ozkan, N., Axon J. C., & Cipcigan, L. (2014). Policy and regulation for smart grids in the United Kingdom. Renewable and Sustainable Energy Reviews, 40, 269-286.

[10] Potter, C.W., Archambault, & A., Westrick, K. (2009). Building a Smarter Smart Grid through Better Renewable Energy Information. Paper Presented at the Power Systems Conference and Exposition, March 15–18, Seattle.

[11] Mah, N. D., Vleuten, M. J., Hills, P., & Tao, J. (2012). Consumer perceptions of smart grid development: Results of a Hong Kong survey and policy implications. Energy Policy, 49, 204-216.

[12] Crispim, J., Braz, J., Castro, R., & Esteves, J. (2014). Smart Grids in the EU with smart regulation: Experiences from the UK, Italy and Portugal. Utilities Policy, 31, 85-93.

[13] Joint Research Center (JRC). (2011). Smart Grid Projects in Europe: Lessons learned and current developments. Institute for Energy.

[14] Faruqui, A., Harris, D., & Hledik, R. (2010). Unlocking the €53 billion savings from smart meters in the EU: How increasing the adoption of dynamic tariffs could make or break the EU's smart grid investment. Energy Policy, 38(10), 6222-6231.

[15] Reckwitz, A. (2002). Toward a Theory of Social Practices: A development in culturalist theorizing. European Journal of Social Theory, 5(2), 243-263.

[16] Parodi, W. G., Krishnamurti, T., Davis, A., Schwartz, D., & Fischhoff, B. (2016). A decision science approach for integrating social science in climate and energy solutions. Nature Climate Change, 6, 563-569.

[17] Fisch, M. N., Wilken, T., & Stähr, C. (2013). Energy PLUS: Buildings and districts as renewable energy source.

[18] Colak, I., Bayindir, R., Fulli, G., Tekin, I., Demirtas, K., & Covrig, F. C. (2014). Smart grid opportunities and applications in Turkey. Renewable and Sustainable Energy Reviews, 33, 344-352.

[19] Bariss, U., Timma, L., & Blumberga, D. (2014). Smart Metering Pilot Project Results. Energy Procedia, 61, 2176-2179.

[20] Goulden, M., Bedwell, M., Egglestone, R. S., Rodden, T., & Spence, A. (2014). Smart grids, smart users? The role of the user in demand side management. Energy Research & Social Science, 2, 21-29.

[21] Faruqui, A., Sergici, S., & Palmer, J. (2010). The impact of dynamic pricing on low income customers. IEE white paper.

[22] Morgan, G. M., Fischhoff, B., Bostrom, A., & Atman, J. C. (2002). Risk Communication: A Mental Models Approach. Cambridge.

[23] Teddlie, C., & Yu, F. (2007). Mixed Methods Sampling: A Typology with examples. Journal of Mixed Method Research, 1, 1-25.

[24] Ministry of Energy (MOE). (2015). National Smart Grid Development Roadmap of Thailand between 2015-2036. Bangkok, Thailand.

[25] Electricity Generating Authority of Thailand (EGAT). (2013). EGAT Smart Grid Development Roadmap between 2013-2032. Bangkok, Thailand.

[26] Provincial Electricity Authority (PEA). (2015). PEA Smart Grid Roadmap Revision Aligned with National Policy between 2016-2036. Bangkok, Thailand.

[27] Metropolitan Electricity Authority (MEA). (2012). MEA Smart Grid Roadmap between 2012-2051. Bangkok, Thailand.

[28] Verbong P. J. G., Beemsterboer, S., & Sengers, F. (2013). Smart grids or smart users? Involving users in developing a low carbon electricity economy. Energy Policy, 52, 117-125.

[29] Energy Policy and Planning Office (EPPO). (2000). Electricity supply industry reform and Thailand power pool. Ministry of Energy, Bangkok, Thailand.

[30] Wattana, S., Sharma, D., & Vaiyavuth, R. (2008). Electricity Industry Reforms in Thailand: A Historical Review. GMSARN International Journal, 2(2), 41-52.

[31] Wisuttisak, P. (2010). Regulatory framework of Thai electricity sector, Australian school of business. The university of New South Wales, Sydney Australia.

[32] International Energy Agency (IEA). (2011). Smart Grid-Smart Customer Policy Needs. Paris, France.

[33] Greacen, S. C., & Greacen, C. (2004). Thailand's electricity reforms: privatization of benefits and socialization of costs and risks. Pacific Affairs, 77(3), 517-541.

[34] Energy Regulatory Commission (ERC). (2016). Retail and wholesale electricity price structure of Thailand. Bangkok, Thailand.

[35] Carroll, J., Lyons, S., & Denny, E. (2014). Reducing household electricity demand through smart metering: The role of improved information about energy saving. Energy Economics, 45, 234-243.

[36] Ofgem. (2011). Energy Demand Research Project: Final analysis. UK.

[37] Energy policy and Planning Office (EPPO). (2016). Demand response: DR100 program pilot project. Ministry of Energy, Bangkok, Thailand.

[38] Hargreaves, T., Nye, M., & Burgess, J. (2013). Keeping energy visible? Exploring how householders interact with feedback from smart energy monitors in the longer term. Energy Policy, 52, 126-134.

[39] MECON Project. (2014). Effective energy efficiency policy implementation targeting “New Modern Energy Consumer” in the Greather Mekong Sub-region. Bangkok, Thailand.
[40] Chmutina, K., & Goodier, I. C. (2014). Alternative future energy pathways: Assessment of the potential of innovative decentralised energy systems in the UK. Energy Policy, 66, 62-72.

- empty page -